THE MANUFACTURE AND USE OF PLYWOOD AND GLUE

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PUBLISHERS' NOTE

The materials for this book have in the main already appeared in *The Aerial Age*, but the whole work has been supplemented and rearranged to make a homogeneous whole. Although originally intended for the use of the aircraft industry, the subject-matter is so complete as to be of great value to all branches of industry interested in woodwork. The present developments in joinery, cabinet-making, coach-building, and allied trades can be readily traced to the valuable experience resulting from aircraft war work; but until the publication of this volume no reference work on this subject existed for the future guidance of those trades or the aeronautic industry. The whole field of the manufacture, uses, and properties of plywood has been covered, and in the section of glues many war developments have been recorded for the first time.

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THE MANUFACTURE OF VENEER AND PLYWOOD

THE development, during the past year, of plywood in its application to aeroplane construction has been greater than that of any other material. Previous to 1918 plywood had been used more or less successfully in fuselage work, and in a somewhat crude way in rib construction. At that time but little definite information was available regarding its properties, design, or the method of applying it. Since then a great deal of experimentation has been carried on by several of the leading manufacturers of plywood and by the U.S. Government, both at McCook Field, Dayton, Ohio, and at the Forest Products Laboratory, Madison, Wis. As a result of their work the efficiency of this material, especially in fuselage and rib construction, has increased more than 100 per cent., and several new applications for it have been developed. The processes used in the manufacture of veneer and plywood are therefore of unusual interest to the aircraft designer and builder.

In the veneer industry there are two distinct manufacturing operations—the cutting of the log into thin sheets, known as veneer, and the building up of this veneer into plywood. The larger plants, as a rule, carry on both these operations simultaneously, but at the present time there are many factories devoted wholly to the cutting of veneer, while others specialize in the manufacture of plywood. Woods which are most used for veneer are birch, poplar, basswood, spruce,

Spanish cedar, maple, mahogany, walnut, gum, ash, and oak. For aeroplane work different species are often used in combination in plywood, depending on the properties that are desired.

As the logs are unloaded at the veneer mill they are separated according to their variety. Although it may often be impossible to cut up the logs immediately, an important principle in regard to their storage is that the sooner a log is made into veneer after being taken from the living tree the better will be the results. Season checks and cracks have less opportunity to develop. Decay, particularly in the heartwood and along the season checks, is largely prevented, and therefore much waste in sawing off the ends of the logs is eliminated. But especially for ease in cutting the veneer in the slicer and rotary cutter is it desirable to have the logs fresh and full of sap. This condition is most important in the case of gums, maples, birches, and woods with sweet sap.

Methods of Cutting

The three general processes by which veneer is produced from the log are rotary cutting, slicing, and sawing. Of these methods the most important is rotary cutting, in which the log is placed in a large lathe and the veneer cut tangentially in a continuous sheet. About 70 per cent. of all veneer, including all the cheaper grades, is cut in this manner. The finer woods like walnut, maple, and mahogany are usually quarter cut, that the full beauty of the grain may be obtained. In this case slicing or sawing must be resorted to. However, some logs of gum and poplar give bastard (tangential) cuts of very striking figure. Where quarter-cut veneer thinner than $\frac{1}{32}$ inch is desired it must be cut by a slicer. Small logs of the more expensive woods, that would be quarter cut if possible, must be rotary cut in order to get widths which are of any value.

The preparation of the logs varies with the process used. For slicing and rotary cutting steaming is required, while for veneer sawing and slicing it is necessary to saw the log longitudinally into a number of wedge-shaped pieces.

Rotary Cutting

With all woods which contain frost, or which are dry, steaming is necessary, as it is with the harder woods, but unless the thickness of the veneer exceeds about $\frac{3}{16}$ inch most soft species that are fairly fresh may be rotary cut without preliminary steaming. (A description of steaming bins and the routine followed in the process will be given later in connection with slicer cutting.) As the logs come from the steam bins they are barked, and any irregularities on the surface, such as projecting swellings or overgrown limb stumps, are trimmed

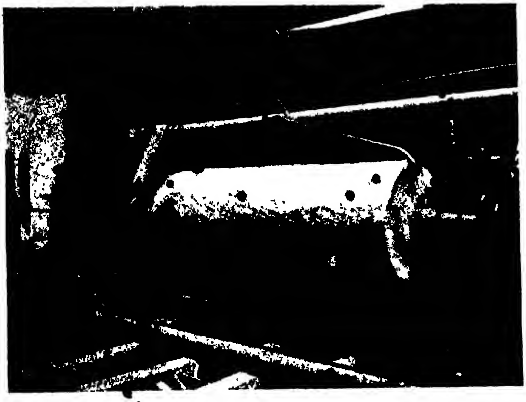

FIG. 1.—CENTRING OF LOG IN ROTARY CUTTER.

off. They are then cut to the desired length in a large cross-cut saw and the ends squared. The centre of each end is carefully located and then the log is picked up by a derrick, swung into position, and centred in the rotary cutter, as shown in Fig. 1.

A cutter of this type is in effect a huge wood-turning lathe, with a long stationary knife fixed in position behind the log, its cutting edge at the same elevation as the axis of the chuck and spindle. Fig. 2 shows clearly the relative arrangements of the parts. The spindle into which the chuck fits is threaded

for part of its length, so that when turned by a certain train of gears it advances and drives the spurs into the ends of the log, which must be very firmly gripped. Slightly forward of and above the main blade will be noticed several small adjustable knives in planes at right angles to the long knife. These are for the purpose of cutting the sheet of veneer into whatever lengths are required. The points of these knives meet the log just before it reaches the horizontal knife and cut shallow, narrow grooves around its circumference. The size of chuck used depends partly on the diameter of the log

FIG. 2.—FRONT VIEW OF ROTARY CUTTER.

and partly on the amount of decay in the heartwood. The spurs must obtain a hold in sound wood. Since the smallest chuck is 6 inches in diameter, at least $6\frac{1}{2}$ inches of log must necessarily be wasted. But, owing to the unsoundness that is usual in heartwood, this is but a slight disadvantage. In fact, it might be mentioned in passing that one of the important advantages of rotary cutting over slicing or sawing is the small influence that centre decay has on the value of a log. For in the latter processes the log must be sawn into sectors, and serious decay at the centre very materially reduces the width of the sheet that can be obtained.

The sheet of veneer comes out at the back of the machine, through a slot just below the edge of the long cutting knife, as shown in Fig. 3. The rate at which the veneer is cut varies as the diameter of the log because the rotary speed of the cutter, though slightly lessened when the load is excessive, is approximately constant at about 28 r.p.m., giving to the log a peripheral velocity depending on its size.

Veneer Sizes.—The maximum length to which veneer may be cut is limited by the size of the knife. The greatest length in use at the present time is 16 feet; however the majority

FIG. 3.—REAR VIEW OF ROTARY CUTTER.

of knives are less than 8 feet 6 inches. With a long log the pressure of the knife acting on a large unsupported length tends to cause the log to chatter near its centre. For this reason greater wastage occurs owing to the impossibility of cutting the log to a small diameter. The sheet of veneer may be cut to any desired width if care is used to avoid breaking it in handling. Widths of 20 to 30 feet should be obtained without difficulty unless the veneer is very thin. In the preceding description the term "length" refers to the dimension parallel to the direction of the grain, and the term "width" to that perpendicular to this direction. With soft

woods, thoroughly steamed, veneers up to $\frac{3}{8}$ inch thick may be obtained, though a better maximum is $\frac{5}{16}$ inch. In the case of oak, mahogany, or maple not more than a $\frac{1}{4}$-inch thickness can be expected. On the other hand, these harder woods, with a tough fibre and fine grain, can be cut to a minimum thickness of $\frac{1}{64}$ inch, while for poplar and gum $\frac{1}{32}$ inch is a minimum value. Minimum thicknesses are limited chiefly by breakage in handling, and during the past year special methods have been devised that partly remedy this difficulty.

The crew of a rotary cutter consists of five men, including one operator and two chippers. The latter catch the veneer as it falls from the knife, carry it back from the machine until the required width is reached, and then cut it off. It is necessary to obtain a given dry width, to allow for a certain shrinkage from the wet width. This increase for gum is $1\frac{1}{2}$ inches per foot, for poplar $1\frac{1}{4}$ inches, and for oak 1 inch. The other two men of the crew are needed for the work of steaming and preparing the logs.

Preparation of Logs for Sawing and Slicing

Steaming.—If logs are to be cut into veneer on a slicer they must first be steamed. This operation is carried on in large bins which, if below ground, are generally of concrete; if above ground, of wood with walls 6 or 7 inches thick. The rough logs are lowered by a derrick into these bins, on which heavy wooden covers are then placed and tightly clamped down. Steam is now turned on. Most woods, except oak and mahogany, require steaming only over night, but with the latter 18 hours is usually needed. The size of the logs and the amount of frost they contain are factors in determining the duration of the steaming and the pressure necessary. For poplar, gum, and walnut low-pressure steam is sufficient, while the denser, harder woods must have steam under somewhat greater pressure. If the operator desires to accelerate the process he may do so by employing higher pressures. Some latitude is permissible in both the time and the pressure, and the operator may exercise his judgment. In all cases the

frost must be taken out, and after that a few woods, like walnut, unless fairly dry, need only warming through.

Sawing the Logs.—The logs are first barked and trimmed, and then placed on the carriage of a large band saw, so that

FIG. 4.—BAND SAW CARRIAGE.

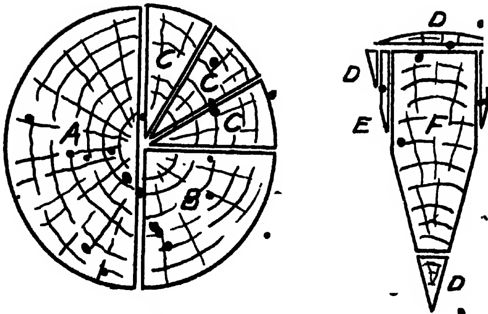

FIG. 5.—METHOD OF CUTTING LOGS.

the saw will pass directly through the centre of the log at each end. The carriage is seen in the foreground of Fig. 4 in its relation to the edging saw at the extreme left, and the veneer saws in the background. The sawyer next determines into how many "cants" or "pies," C, (Fig. 5) it is best to cut

each half of the log, his decision being based on the size and location of any defects that may be present on the diameter of the log, and on the width of the veneer desired. The cants are held by dogs on the carriage and trimmed to the flitch "F" by cutting off the corners "D," the heart, if defective, and one or two boards "E." Frequently it is necessary to saw the entire cant into boards if it appears unsuitable for veneer. The boards "E" are taken at once to the edging saw and trimmed. The waste parts are generally removed and used for fuel. The flitch "F" is now ready for either the veneer saws or the slicers.

For all quartered work the log is so placed that the cuts are radial. Occasionally, however, as with walnut, gum, or poplar, in which there is no special quartered figure, flitches are prepared for bastard sawing or slicing.

A band-saw crew consists of four men: the expert sawyer and three helpers, one of whom runs the edging saw for trimming up the boards.

Slicer Cutting

This process is not in such extensive use as either rotary cutting or veneer sawing, yet it has certain advantages within its own field. The chief of these, perhaps, is that the entire flitch can be utilized, whereas in veneer sawing, in spite of the thin saw employed, from 30 to 60 per cent. is wasted in saw kerfs. This becomes an important item when the wood is an expensive mahogany, curly maple, or walnut. Again, if quartered veneer less than $\frac{1}{30}$ inch thick is desired it must be cut on a slicer, for that is a minimum thickness for veneer sawing.

In slicer cutting the wood is sawn into flitches, as described above, for either quarter or bastard slices. Soft woods like poplar, especially when full of sap, do not require steaming, unless the veneer is more than $\frac{1}{16}$ inch thick. Other woods, in a similar condition, need not be steamed if less than $\frac{1}{32}$ inch thick, but all wood when full of frost or when dry must be steamed, particularly oak and mahogany

Reference to Fig. 6 will help to make clear the construction of a slicer. It consists of two principal parts—the stay log, a heavy casting with a broad vertical face with grooves in which are mounted adjustable dogs that grip the flitch, and opposite this a heavy ribbed casting holding the knife. The stay log, with the flitch, is given a reciprocating motion that is forward and downward in its positive direction while the knife is stationary and slightly inclined upward with the cutting edge of the blade up. The knife is narrow, ordinarily not more than 14 feet long, and rapidly increases in thickness

FIG. 6.—FRONT VIEW OF SLICER.

from the cutting edge to give a strong and rigid backing to the latter. Through a "pressure bar" running parallel to the knife, and regulated by a hand wheel, the thickness of the veneer is controlled. This wheel is graduated along the rim, and turns past an index. One complete turn increases or decreases the thickness $\frac{1}{2}$ inch and fractional turns change the thickness proportionally. It is impossible to cut the entire flitch into veneer, as about $\frac{3}{4}$ inch is required by the dogs that grip the flitch. If the latter is heavy or of very hard wood this unused width often increases to 1 or $1\frac{1}{4}$ inch.

Veneer Sizes.—The maximum length of flitch that can be

handled is determined by the length of knife in use, which is usually 12 to 14 feet, rarely as much as 18 feet. The softer woods may be cut to a thickness as great as $\frac{3}{4}$ inch when thoroughly steamed. The ordinary minimum thickness for any work is $\frac{1}{96}$ inch, which, by careful adjusting, alignment, and sharpening of the knife, may be decreased to $\frac{1}{120}$ inch. Of course, only hard, fine-grained woods can be used for very thin veneer, with the exception of Spanish cedar. The maximum width is two feet. However, when great widths are wanted the maximum length is decreased somewhat.

FIG. 7.—VENEER SAW AND FLITCHES

Three men compose a slicer crew: the operator at the wheel regulating the pressure bar, and two helpers who place the strips of veneer on a table as they fall from the knife.

Veneer Sawing

This process, possibly because of its simplicity, is more widely used than slicing for the production of quartered veneer. As is illustrated in Fig. 7, the flitch is firmly held by numerous dogs or clamps which slide up and down in grooves in a heavy stay log. This stay log, like the usual carriage of a saw, travels back and forth, carrying the flitch against

the saw. This is circular with its cutting edge made up of several segments of thin steel securely bolted to the heavier steel casting which stiffens and supports the cutting segments. A kerf $\frac{1}{16}$ inch wide is made by such a saw and, as in a slicer, at least $\frac{3}{4}$ of an inch of the flitch is required for the dogs to grip.

The sheets of veneer as they are sawn off are piled in order, and when the flitch is finished the top sheet is marked with the number of the log for purposes of later identification, a procedure which is also followed with veneer cut in a slicer.

Veneer Sizes.—The maximum length it is possible to cut is dependent on the extreme travel of the stay log. With some saws this is 24 feet, but 14 to 16 feet is the more usual limit of travel. A minimum thickness is $\frac{1}{32}$ inch, though in ordinary practice $\frac{1}{28}$ inch is better. A maximum width is about 18 to 20 inches. Since for quartered work the diameter of the log must be at least twice the width of the veneer, and if the heart is unsound as much as three times the width, it can be seen that for veneer sawing large and consequently expensive logs are used.

Three saws, with a total crew of five men—one expert, two sawyers, and two helpers—constitute an efficient working unit. Since two men are required to operate a saw most effectively, and since it frequently happens that one of the saws has to be stopped for repairs or sharpening, this arrangement makes it possible to keep two saws busy continuously, with the expert occasionally running a third. A band-saw crew of four men is able to turn out enough flitches to keep such a unit supplied.

Drying Veneer

After the veneer has been cut by one of the three methods which have been outlined it is generally green and wet with steam, and must be thoroughly dried before being either stored or made into plywood. The drying process is a very simple one. It consists merely in drawing air, which has been dried and heated by passage over steam pipes, through the room or rooms in which the veneer is stacked. A tem-

perature of 100 to 110 degrees Fahrenheit is maintained. When the air has become nearly saturated with moisture from the veneer it is sucked out by fans that keep up a continuous circulation. A drying period of from 12 to 13 hours is sufficient, as a rule, for veneer which does not exceed $\frac{1}{16}$ inch in thickness, and for greater thicknesses a proportionately longer time is necessary.

Stacking Veneer.—It is most important that the sheets of veneer be so stacked as to insure a ready access of air. The methods employed depend largely on the size and shape of the stock. The comparatively long and narrow sheets from the veneer saws or the slicer are placed in "tooth racks" which consist of pickets about 30 inches long placed in pairs, their lower ends fitted into mortises cut in a piece of scantling so that the clear space between them is $\frac{1}{4}$ inch. The veneer is supported every 2 or 3 feet by these pickets. Unless the sheets are fairly thick two are placed back to back in these racks, and if they are not more than 12 to 15 inches wide they may be stacked edge on edge, two or more deep. The air has always full access.

What is known as the "protected end" method is employed when the sheets are wide and short—that is, not more than 3 feet long. Light boards with vertical grooves cut in them every 3 or 4 inches replace the pickets. The distance between these parallel boards or holders is varied according to the length of the veneer sheets, which are slipped into the grooves. In this way the ends of the sheets are protected, or prevented from cracking and warping while drying.

For rotary-cut veneer—which for the most part is short and very wide—a third method called the "hanging process" is used. Lengths of from 6 inches to 3 or 4 feet, or even more, and widths of any dimension can be handled. Pairs of parallel wires, spaced 15 inches apart, are strung across the room about 5 feet above the floor. Each pair of wires supports a number of light wood cross members that project a little below the wires, and near their lower edge are driven nails which project an inch on each side of the stick. The sheets

of veneer are hung from a cross-stick by these nails, which are struck through the piece close to its upper edge. When the width of the sheet is greater than the distance of the wires from the floor it is folded, and the other edge of the sheet is supported by the nails on the opposite side of the cross-stick. Very wide sheets and lengths greater than 20 inches are ordinarily suspended from two or more sets of wires.

After the veneer has been dried it is taken either directly to the cutting and gluing rooms to be made into plywood or to the storeroom for future use. Here it is kept in low piles containing all the veneer cut from one log, and marked with the log number. Since it may have absorbed some moisture while in the storeroom, veneer, before it can be used, must first be put through a redrying press. Such a press consists of a series of heavy, hollow iron plates, sliding up and down in an open steel frame, heated by live steam and forced together both by their own weight and by the pressure of steam acting on a piston. Only 5 or 10 minutes are necessary to complete the redrying of veneer of the usual thickness. Lack of care in this operation may cause a glossing of the surface of the veneer that is apt to render gluing difficult.

The Manufacture of Plywood

The first step in the manufacture of plywood is to cut the sheets of veneer to gross lengths and widths which are such that an ample allowance is made for later trimming to the exact dimensions specified in the order to be filled. Uniformity and speed are secured by the use of double header saws, both cross-cut and rip. With sawn or sliced veneer the sheets are usually so narrow that two or more must be spliced together.

Jointing and Splicing.—To secure square, straight edges the sheets are put through a jointer. A sufficient number to make a thickness of 3 inches are placed on the bed of this machine and are carried over a knife, gripped between a series of rolls and a roughened, endless chain. But one man is needed for the operation of a jointer. The veneer now

passes to the splicer, where enough sheets are joined to give the required width. The operator takes up two pieces of veneer, places them on the smooth bed of the splicer, and, pressing the edges together, starts the sheets under a roller which forces them still closer. At the same time a strip of gummed paper an inch wide is moistened and drawn through the roll with the veneer. This serves to fasten the pieces together. It is applied only to the outside surface of the outer plies of veneer, because if it were used on the inner surfaces of the plies the panel would not be waterproof. No glue whatever is applied to the joint, which is perfectly flexible. In a panel the inner layers of veneer, for which, as a rule, the softer, cheaper woods are used, do not need splicing, as they are rotary cut and hence can be of any width. Two men are necessary to run a splicer.

Gluing up Panels.—The operation next in order after the splicing is that of gluing up the veneer to form a "panel" or "plywood." The "finish" or outside "plies" of panel that have just come from the splicer are not put through the gluer. Only the inner layers or "cross-bands" pass through this machine, which applies the glue to both surfaces of the wood. As a "cross-band" comes from the gluer it is laid upon a sheet of finish veneer. When the panel is only three-ply another layer of finish is next placed upon the "core" or cross-bands, with its grain at right angles to the grain of the core, and parallel to that of the first finish ply. If, however, the panel is to be of five-ply construction, a relatively thick core or "centre," usually of chestnut, gum, or poplar, and often of comparatively poor quality, is laid upon the first cross-band; on top of this comes another cross-band, and lastly the outside finish ply. Veneer used for cross-banding is generally the cheaper, rotary-cut gum or poplar, and since it can be obtained in any width, splicing is unnecessary. Panels, of course, may consist of any number of plies. Symmetry requires that the number be odd. Always, the grain of adjacent plies is at right angles.

Pressing the Panels.—The glued panels are now placed in

piles upon a "caull," a thick, rigid board of laminated construction. Between each layer of plywood is inserted a thin waxed board. When the piles are $3\frac{1}{2}$ or 4 feet high another caull is put on the top and the whole then placed in an hydraulic press. But instead of resting directly on the bed of the press the lower caull rests upon several shallow I-beams placed crosswise of the bed. The same number of I-beams are similarly put on top of the upper caull. The I-beams project beyond the sides of the pile and heavy turn-buckle clamps are attached to corresponding ends above and below. The purpose of these clamps is not to aid in applying the load, but as the pile compresses or packs down slightly, air and surplus glue being squeezed out, the slack in the clamps is taken up, and therefore, when the stack is removed from the press, it is still under great pressure caused by tension in the clamps.

The pressure while the stack is in the press depends upon the character of the panels—that is, their size and thickness, and the species of wood of which they are made. For lighter work 100 pounds per square inch is satisfactory, but for the largest, heaviest type, a pressure of 300 pounds per square inch is needed. Excessive compression causes the glue to squeeze out between the joints and results in a "starved" joint. The operation of pressing takes only about 5 minutes.

After removal from the press, the stack of panels, tightly clamped together, is carried to a drying room. Here it remains as a rule for 24 hours in a temperature of 70 to 90 degrees Fahrenheit. When this time has elapsed the clamps are loosened, the upper caull removed, and the panels piled up in the same room, separated by small sticks so that they are entirely exposed to the dry air kept circulating through the room. Forty-eight hours is allowed for this second drying, after which the panels are ready for cutting to size and sanding.

Cutting and Sanding.—This operation is done with rip and cross-cut saws which trim the panels to the specified dimensions. They are now ready for the final process, that of smoothing

the surfaces in a sanding machine. The panels are drawn in by steel rolls and passed over sandpaper of grades ranging from No. 1½ to No. 0. Ordinarily this is sufficient, although sometimes a panel has to be put through the sander a second time. For very fine work a "finish sanding" on a belt re-sander with No. 00 paper is required. Whenever plywood is designed to carry important stresses care must be taken, especially if the face plies are thin, not to remove too much material in the sanding process in order to reach a specified total thickness.

Minor defects that occasionally appear in finishing work, caused, perhaps, by slight imperfections in the wood or careless workmanship, are repaired by an expert, who generally cuts out the part containing the flaw and inlays new wood.

CHAPTER II

THE GENERAL PROPERTIES AND USES OF PLYWOOD

FOR a material combining lightness and strength, wood would be unexcelled if it were of homogeneous structure. In tensile strength parallel to the grain, certain heavy woods like pignut hickory are more than half as strong as mild steel, and their weight is less than one-eighth that of steel. Spruce, a typical light wood, has a fifth the strength of steel, yet only an eighteenth its weight. The same is true, though to a less degree, of the modulus of rupture, and the compressive strength of wood parallel to the grain. However, the tensile and crushing strength perpendicular to the grain, and the modulus of elasticity in this direction, are but a tenth to a twentieth of these values. On the other hand, the resistance of wood to shear parallel to the grain is many times less than its resistance to shear across the grain. Because of these facts, the utilization of the full tensile strength of wood, or of its high modulus of rupture, is made difficult. This is due to the trouble in holding a member by bolts or similar means, to the large bearing surface necessary to prevent crushing of the wood perpendicular to the grain, or to weakness in horizontal shear.

The chief function of plywood is to equalize the strengths of wood in directions at right angles to each other. This is accomplished by cutting the wood into thin sheets, called veneer, which are then glued together to form a laminated structure, composed of a central core, or cross-band, on both sides of which are glued sheets of veneer with their grain at right angles to that of the core. These are the outside or face plies in three-ply panels. In multi-ply construction the

procedure is the same, except that extra plies are added, an equal number on each side of the core, and every ply is placed with its grain at right angles to that of the layer immediately beneath it.

Another very important result obtained by plywood construction is the practical elimination of warping. In ordinary wood, changes in its moisture content produce shrinkage, which is much greater, proportionally, in a direction transverse to the grain than parallel to it. When this shrinkage is unequal on the two faces of a board, owing to more rapid alteration in moisture content on one side, warping occurs. By making the shrinkage in one direction oppose that in the other, properly constructed plywood prevents the difficulties caused by shrinkage. In the more extended discussion that follows is explained the manner in which plywood modifies the properties of natural wood.

Woods Used in Plywood Construction.—On account of the many new uses to which plywood has been put during the war the varieties of woods employed in its manufacture have changed considerably. Extensive testing has brought about the elimination of some species, because of their lack of suitability for structural purposes, and has caused the selection of several of the little-used woods for special work.

The species from which most plywood was made before the war are given below, in the approximate order of their importance: Gum, maple, oak, poplar, ash, basswood, birch, elm, walnut, beech, yellow pine, cottonwood, sycamore, and mahogany. Several woods, notably spruce, Spanish cedar, and redwood, which formerly were seldom used, have been found to be among the best for meeting the requirements of aeroplane construction. The more important properties for structural plywood are lightness combined with high bending and compressive strength, stiffness, and toughness or resistance to splitting. Other qualities which are desirable, but which do not vary greatly in different species, are resistance to distortion, due to variation in moisture content, and ability to take glue well.

Some aeroplane parts call for a very strong, tough wood, and one of the heavier species, like birch or maple, must be employed; while other parts require the qualities of lightness and stiffness together with moderate strength, such as is found in varying degrees in spruce, poplar, basswood, and Spanish cedar.

Factors in the Design of Plywood

Symmetrical Construction.—The first principle governing the construction of plywood is that of symmetry. On either side of the centre layer or core there must be an equal number of plies. The number of laminations in plywood must therefore be always odd. For each ply on one side of the core there must be a corresponding ply in the same relative position on the opposite of the core. Both such plies must be of the same thickness and same species of wood, preferably, cut in the same manner—that is, by a rotary cutter, slicer, or veneer saw. Furthermore, the grain of two layers which are both the same distance from the core, must run in the same direction. The reasons for this manner of construction are in the main connected with the phenomena of shrinkage.

On account of the great difference, with any wood, between the shrinkage parallel to the grain and that perpendicular to it, stresses will always be set up or released in plywood when its moisture content is altered. Considering a three-ply panel, for example, if the humidity increases the core will tend to expand transversely, but since it is rigidly glued to the face plies, in which the grain is at right angles to that of the core, this transverse swelling is checked, on account of the fact that the face plies do not deform appreciably in a direction parallel to their grain. They are therefore put in tension. In a similar way the face plies would expand in a direction perpendicular to their grain were they not restrained by the core, thereby being put under compression. Each one of the three plies is thus subjected to tensile stresses parallel to its grain, and to compressive stresses transverse to its grain.

The application of the principle of symmetry will prevent warping; for it is evident that if the face plies, or with multi-ply wood, all pairs of corresponding, intermediate plies as well, are of the same thickness, density and species, and have their grain running in the same direction, the stresses on either side of the core will be balanced. However, should similarly situated plies be of unequal thickness or character, or not have their grain parallel, either cupping or twisting of the panel will occur. Because of these facts, it is clear that in sanding plywood care must be exercised to sand both faces equally.

An extreme example of distortion results when one of the faces of a thin, three-ply panel has its grain perpendicular to that of the other face ply. If such a panel is dried, it will curl up almost into a cylinder with the ply, whose grain is parallel to the grain of the core, on the inside. This phenomenon is produced by the unsymmetrical distribution of the shrinking stresses. Placing the grain of each face ply at an angle of 45° to that of the core, and of 90° to that of the other face ply, will cause another extreme case. A change in moisture would bring about a twisting or curling up of such a panel in the direction of one of its diagonals.

This discussion makes evident the necessity for having the grain of adjacent plies as exactly at right angles as is practical. Furthermore, to reduce shrinkage stresses to a minimum, it is desirable that the moisture content of the plywood, when the latter is removed from the clamps after gluing, be as closely as possible the same as it will be in actual service.

Owing to the fact that the shrinkage of different varieties of wood, with the same alteration in moisture content, is never identical, the amount of shrinkage in a panel will vary with the species or combination of species used. It is also dependent on the relative thickness of the different plies and the number of plies. A series of 54 shrinkage tests were made recently by the Forest Products Laboratory on combinations of ten of the more common species of wood. The average shrinkage in bringing the panel from the soaked to the over-

dry condition was ·45 per cent. parallel to the grain and ·67 per cent. perpendicular to it. Individual results ranged from ·2 to 1·0 per cent., and from ·3 to 1·2 per cent., respectively. These values should be contrasted with shrinkage, under the same conditions, of 8·5 per cent. for flat-sawn boards and 4·5 per cent. for quarter-sawn lumber, which are average values for 150 species.

Number of Plies.—Several factors must be considered in determining the number of plies it is best to use. The most important effect of increasing the number of plies is to make the plywood more homogeneous. Its strength in both bending and tension in the direction of the grain of the face plies is decreased, while its strength in a perpendicular direction is raised, until the strengths in each direction are nearly equal. Hence, the three-ply type is best if much greater strength is desired in one direction than in another. Approximate equalization of the strengths of a three-ply panel in each direction can also be accomplished by properly proportioning the core thickness. However, in resistance to splitting action, such as is needed when plywood is fastened by screws near its edges, the three-ply can never be made to equal the multi-ply construction.

In general, whenever a joint is made between two thick laminations which have their grain at right angles, there exists a tendency to weakness along the joint. This is also the case with plywood made up of heavy veneer, and is due at least in part to the greater shrinkage stresses that occur with thick plies. The use of fairly thin plies renders less likely the development of weakness along a joint.

Another consideration that is sometimes the controlling factor in deciding on the number of laminations, is that the extra glue required where many thin plies are used adds very appreciably to the weight. This point should always be considered. In case it is especially desirable that the plywood remain very flat, multi-ply construction is advisable. The reason that distortion is practically eliminated is that the shrinkage stresses are more nearly equalized.

Lastly, certain commercial reasons may affect the number of plies. Of these factors, the principal one is the extra labour entailed in the multi-ply type of panel. In certain instances, particularly where the total thickness of the plywood is small, the maximum number of plies is limited by the minimum thickness to which it is practicable to cut veneer. This varies with the hardness of the wood, the closeness and nature of its grain, and the method employed in cutting the veneer. For rotary cutting $\frac{1}{48}$ inch is a usual minimum, and for slicing $\frac{1}{80}$ inch. Because of the difficulties in handling very thin veneer, the widths of such sheets are usually limited. Species of low density and open structure cannot as a rule be cut less than about $\frac{1}{32}$ inch thick.

Ratio of Core to Total Thickness.—As suggested before, the strengths of plywood in directions parallel and transverse to the grain of the face plies may to a large extent be modified by the ratio of the core to total thickness. The term core is here meant to include all the layers whose grain runs perpendicular to that of the faces. The purpose for which the plywood is intended largely determines this ratio of core to total thickness. For example, to obtain the same tensile strength in each direction, the core should be ·5 the plywood thickness, while for equal strengths in bending this proportion should be ·7. However, the presence of shrinkage stresses may introduce an uncertainty that upsets any calculations. A large proportion of core laminations is effective in reducing any tendency to distortion.

Low Density Species for Cores.—The strength of a panel subjected to tensile stresses parallel to the grain of the faces is independent of the nature of the core. On the other hand, the modulus of rupture and the column strength may be very largely affected, owing to the fact that these properties are proportional to the moment of inertia of the cross-section of the panel. Of two cores, equal in weight but differing in density, the low density core will be the thicker, and hence will space the outer plies further apart. Experiments have shown that plywood in carrying an axial load acts like a

long column whose capacity is a function of its slenderness ratio. From this it is apparent that any increase in the spacing of the face plies, secured by using a thick, low density core of basswood or poplar, will add appreciably to the column strength parallel to the grain of these plies. It should be carefully noted, however, that this increase in strength is due solely to the greater distance between the effective plies, and not to the character of the wood in the core.

In general, for large column strength the face plies should be thin, and of a strong wood like birch or maple, and be separated as far as possible. This same disposition of material will add to the resistance of the plywood to cupping and twisting.

In this connection the Forest Products Laboratory found in its tests that panels constructed of low density woods were less inclined to distort than those built up of species of high density. This slightly greater tendency to warp must be balanced against the better structural characteristics of a panel with strong face plies. It might also be added, that tests have indicated no difference in the tendency to warp of wood cut by a slicer or rotary cutter, but sawn veneer will usually warp the least.

Total Thickness of Panel.—Several thousands of tests on plywood of eight thicknesses, varying from $\frac{3}{50}$ inch to $\frac{1}{2}$ inch total, and including all the common species, give data on the effect of panel thickness upon the various physical properties of plywood. All the specimens in the tests were of rotary cut veneer, and each panel was three-ply, with all the plies of the same thickness. It was shown that the panel thickness has no effect on the unit, tensile strength. That portion of the material in which the grain was perpendicular to the direction of stress for the most part influenced the strength very slightly. The unit tensile strength parallel to the grain was $1\frac{1}{2}$ to 2 times as great as that transverse to the grain.

Tests on the column-bending modulus (P/A+My/I), a property analogous to the ordinary modulus of rupture fo

bending, brought out somewhat different results. When the load was applied perpendicular to the grain of the face plies this property was constant for all thicknesses. But, with the load applied parallel to the grain of the face plies, a considerable uniform increase in the modulus occurred as the panel thickness was increased from $\frac{1}{10}$ inch to $\frac{1}{2}$ inch. For all the common varieties of wood the total increment amounted to from 29 to 31 per cent. of the value of the modulus when the thickness was $\frac{1}{10}$ inch. The ratio of the column-bending modulus with the load applied parallel to the grain, to that when the load was perpendicular to the grain, varied from 4 to 5. The difference between the unit column loading (*i.e.*, the direct compressive stress, P/A) in these two directions was even more marked. For this case the ratio between the column loads parallel and perpendicular to the grain of the face plies, supported by two panels of the same length and sectional area, varied between 10 and 14, according to the species of wood. The variation, with the panel thickness, in the total load carried was found to follow the law for slender columns and was proportional to the cube of the panel thickness and the square of the column length.

Those tests made on panels constructed of two species of wood in combination demonstrated that the properties of plywood panels in the direction in which the load is applied are dependent entirely upon the character of the plies whose grain is parallel to this direction. For instance, irrespective of whether the core is of high or low density, provided its thickness is the same, the column-bending modulus, the unit column loading, and the tensile strength of a panel are high if the face plies are of a strong, tough wood. And if the panel has a low density core and is subjected to a load transverse to the grain of the face plies, the properties will all be as low as if the face plies were of no stronger wood than the core.

Resistance to splitting, as determined by the total work per inch thickness necessary to cause failure, increases to a certain extent as the panel thickness becomes greater. This

property is of importance if screws or nails near the edge of plywood must be relied upon to hold it securely.

The cupping and twisting of a panel, of a thickness greater than $\frac{1}{4}$ inch, is small and nearly constant. But with decreasing thickness the distortion grows large and variable.

Glued Joints and Splices

The Forest Products Laboratory has also conducted a number of tests on three-ply panels made up of $\frac{1}{16}$-inch basswood and sugar maple veneer, to determine the most efficient types of splices and joints. Two series of tests were made. In the first series two kinds of joints were employed, the diagonal butt and the simple scarf. Some of the panels had a diagonal butt joint in both faces, and some in the core only. For this first series the scarf joints were all in the core. In the second series of experiments splices were made in one face ply only. They were of three types: the simple scarf, the diagonal scarf, and the saw-tooth butt joints. All tests were made in column bending, the results being expressed in terms of the column-bending modulus. All the panels in the first series were 5×12 inches; those in the second set 5×20 inches. The panels were all tested with their long dimension parallel to the direction of the load.

Effect of Slope.—The experiments on all-maple panels with a diagonal butt joint in each face indicated that the strength of such a joint increases progressively with its slope. For example, when the slope was 4 to 5 the efficiency of the joint was 20 per cent. This was brought up to 57 per cent. when the slope was 12 to 5. In the case of the all-basswood panels, the corresponding efficiencies for slopes of 4 to 5 and 12 to 5 were 41 per cent. and 100 per cent., respectively. In these two sets of tests the load was applied parallel to the grain of the face plies.

With the maple panels in which a diagonal butt joint was used in the core the efficiency, with a slope of 4 to 5, was 86 per cent., and it increased to 100 per cent. with a slope of

8 to 5. In the case of basswood panels, however, 100 per cent. efficiency was obtained with the minimum slope of 4 to 5.

A simple scarf joint in the core having a length of 0·7 inches, which gives a slope of 1 to 11, had an efficiency of 85 per cent, for both maple and basswood panels. Had the length of the scarf been 1¼ or 1½ inches the joint would very probably have been 100 per cent. efficient. In all of these tests made on core splices the load was applied parallel to the grain of the core ply.

For the second series of tests the simple scarf joints were

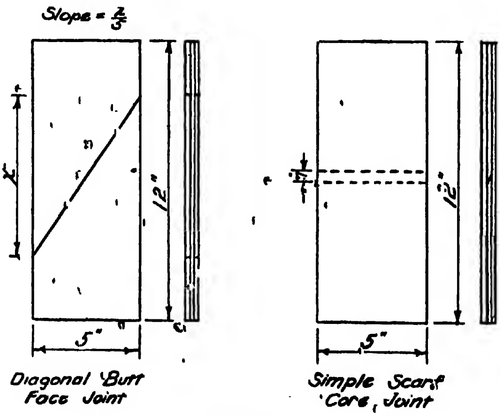

Fig. 8.

¾, 1¼ and 2 inches long, corresponding to slopes of 1 to 12, 1 to 20, and 1 to 30. All the panels in this series had basswood cores. The ¾-inch simple scarf joint with maple faces was 59 per cent. efficient, the 1¼-inch joint 93 per cent., and the 2-inch joint 100 per cent. The corresponding joints with basswood faces were 40, 100 and 100 per cent. efficient. When a diagonal scarf joint 1 inch long was used, the efficiency increased somewhat as the slope of the joint became greater, but in neither the maple nor the basswood panels did the diagonal scarf show any improvement over the simple scarf.

Not until the slope was 12 to 5 did this joint give 100 per cent. efficiency.

The general results of tests on saw-tooth butt joints were the same for both maple and basswood panels. A joint in which the ratio of width of tooth at the base to length of tooth was 5 to 5 proved to be about 40 per cent. efficient, and as the ratio was decreased to 5 to 13 the efficiency rose to

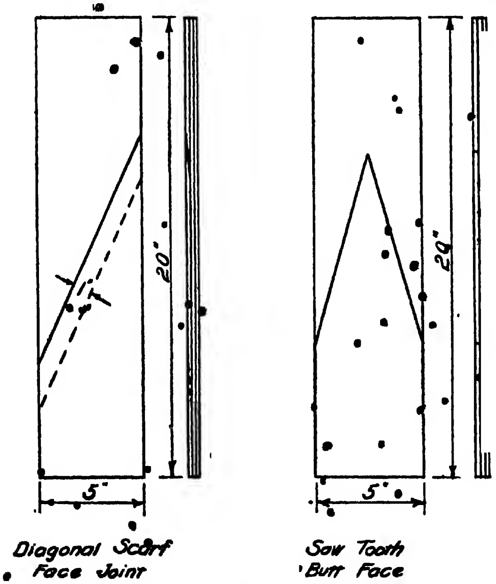

FIG. 9.

80 per cent. In every test made on this type of joint failure occurred in the glue. With both the saw-tooth and diagonal butt joints there was always a strong tendency for the point to separate from the core that was particularly noticeable in panels having maple faces.

In summarizing this discussion, it may be said that the saw-tooth joint is the least satisfactory of any of the types investigated, while the diagonal butt joint is not as good for

most purposes as the simple scarf joint. The latter is superior to the diagonal scarf and can be made 100 per cent. efficient. The most effective length for a simple scarf joint in a $\frac{3}{16}$ inch panel is $1\frac{1}{2}$ inches, which corresponds to a slope of 1 to 25. Figs. 8 and 9 illustrate the various kinds of joints tested.

Riveted Joints

Before it had been demonstrated that glued joints were much more satisfactory, except in special cases, than riveted plywood joints, extensive tests had been conducted on this

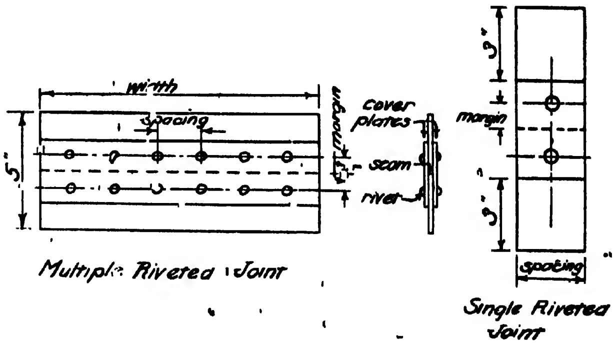

FIG. 10.

type. But a brief discussion will be given of the results of this work. When the spacing of the rivets and the width of the margin are most efficient, the particular size of rivet used has no appreciable effect on the strength of the joint. Since, however, small rivets give their best values for a close spacing, a larger number of them is necessary. This causes much extra work when the smaller sizes are used. On the other hand, the largest rivets require only a third the number of holes and yet make as strong a joint. They are therefore generally to be recommended.

As a material for rivets, aluminium has the advantage over copper or steel due to its lightness, malleability, and the fact

that it gives a tight fit when slightly upset. The tubular form of rivet is superior to the solid unless the size is very small.

The spacing of $\frac{5}{8}$-inch rivets should be about $1\frac{1}{4}$ inches centre to centre, and the margin, or distance between the joint and the centre line of the row of rivets, should be not less than $1\frac{1}{2}$ inches. A margin of $1\frac{3}{4}$ or 2 inches is recommended if the grain of the faces is perpendicular to the seam. For 0·15-inch copper rivets the best results were secured with $\frac{1}{2}$-inch spacing and 1-inch margin. Fig. 10 illustrates the single and multiple rivet types of joints tested.

All of these tests were made on joints with either a single rivet or a single row of rivets. For this reason no conclusions can be drawn or recommendations made relative to joints in which two or three rows of rivets are used. The kind of joint investigated was the butt type with two veneer cover plates. Veneer cover plates are probably best, though where the joint is exposed, the air resistance can be reduced by the use of sheet aluminium and by countersinking the holes so that the rivets will not protrude. The finished joint may be covered with cloth, glued on and varnished. When the grain of the outer plies is perpendicular to the seam the efficiency of the best riveted joints is about 30 per cent.; when the grain is parallel to the seam this value rises to about 50 per cent.

CHAPTER III

PLYWOOD STRENGTH TABLES

THE very large amount of data available on the strength and other properties of all common varieties of wood when made up into plywood panels of varying thickness, number of plies, ratio of core thickness to total thickness, and combinations of species, has been collected and summarized in several tables which are reproduced herewith. The woods used in the tests from which these tables were calculated came from various parts of the country, so that slight variations due to locality are eliminated.

Column Tests.—Tests to determine the column-bending modulus were made on specimens 5×12 inches in size. In order that the panel could be computed as a round-ended column, its ends were rounded into a semicircle. The modulus is calculated by the formula: $S = P/A + 6m/Cd^2$, in which:

S=Column-bending modulus.
A=Gross area of cross-section.
P=Load at maximum moment.
M=Maximum bending moment.
Px=maximum deflection.
B=Width of test piece.
D=Thickness of test piece.

Like the modulus of rupture in the ordinary bending test, the column-bending modulus is not a true stress existing in the fibres at the instant of failure, because the elastic limit has been exceeded, but is rather a measure of the comparative strength of plywood in resisting external bending moments. This property includes two factors, a compressive stress and

a bending stress, but the former is relatively so small that the column-bending modulus can be used and treated as the modulus of rupture.

In connection with the unit column loading or P/A factor in a column test, a series of experiments were made on plywood

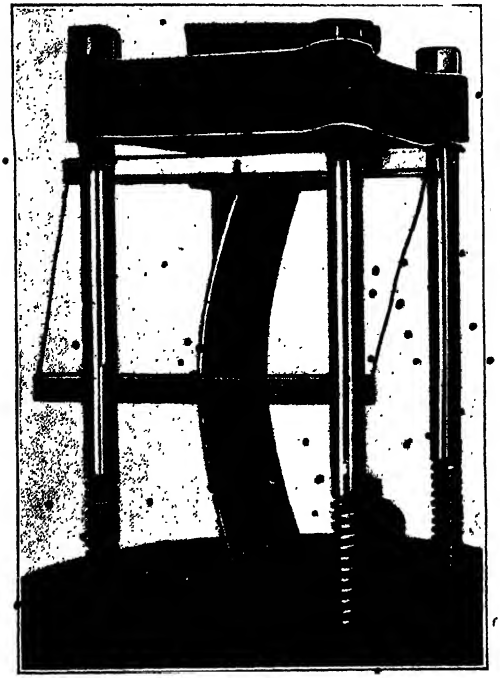

FIG. 11.—A PLYWOOD COLUMN READY FOR TEST.

of various thicknesses to determine whether for a given slenderness ratio the length of a plywood column had an effect on its column strength. It was found that the length had no appreciable effect for a large range of values of the ratio of the length of the column to its least radius of gyration Fig. 11 shows a plywood column ready for this test.

TABLE I.—TENTATIVE TABLE OF STRENGTHS OF VARIOUS 3-PLY PANELS.

ALL PLYWOOD WAS 3-PLY WITH THE GRAIN OF SUCCESSIVE PLIES AT RIGHT ANGLES. ALL PLIES IN ANY ONE PANEL WERE OF THE SAME THICKNESS AND OF THE SAME SPECIES. EIGHT THICKNESSES OF PLYWOOD RANGING FROM $\frac{3}{80}$ TO $\frac{3}{8}$ IN. WERE TESTED.

Species.	Average Specific Gravity of Plywood.†	Average per Cent. Moisture.	Column-Bending Modulus.				Tensile Strength.				Split Resistance.		Modulus of Elasticity.	
			Parallel.*		Perpendicular*		Parallel.*		Perpendicular*				Parallel.*	Perpendicular.*
			No. of Tests.	Lb. per Square Inch.	No. of Tests.	Lb. per Square Inch.	No. of Tests.	Lb. per Square Inch.	No. of Tests.	Lb. per Square Inch.	No. of Tests.	Per Cent. of Birch Resistance.	Lb. per Square Inch in Bending.	Lb. per Square Inch in Bending.
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Birch, yellow ..	0·67	8·5	195	16,000	200	3,200	200	13,200	200	7,700	[illegible]00	100	2,259,000	197,000
Ash, black ..	0·48	9·2	80	7,360	80	1,620	80	6,200	80	3,940	160	68	1,028,000	87,000
Ash, commercial white	0·61	10·6	160	9,980	160	2,640	160	6,540	160	4,330	320	72	1,420,000	144,000
Basswood ..	0·41	9·6	160	6,520	160	1,540	160	6,300	160	4,100	320	65	1,213,000	85,000
Beech ..	0·67	8·6	120	15,390	120	2,950	120	13,000	120	7,260	240	76	2,149,000	167,000
Cedar, Spanish ..	0·41	13·3	115	6,460	115	1,480	115	5,200	115	3,340	230	60	1,032,000	84,000
Cherry ..	0·49	9·9	40	11,180	40	2,220	40	6,920	40	5,650	80	86	1,448,000	150,000
Chestnut ..	0·43	1[illegible]7	40	5,160	40	1,110	40	4,430	40	2,600	80	74	744,300	75,000

Cottonwood	0·48	9·5	40	8,110	40	1,660	40	7,540	40	4,500	80	94	1,461,000	110,000
Douglas fir	0·45	8·4	105	8,860	110	1,730	110	5,630	110	3,530	220	59	1,316,000	129,000
Elm, cork	0·59	11·7	35	10,530	35	2,160	35	9,840	35	6,010	70	100	1,729,000	125,000
Elm, white	0·53	8·9	120	8,810	120	1,900	120	6,460	120	4,180	240	85	1,230,000	112,000
Gum, red	0·54	8·5	102	9,330	102	1,830	102	7,780	102	4,880	204	68	1,487,000	107,000
Gum, cotton	0·49	10·3	80	7,770	80	1,580	80	6,260	80	3,770	160	60	1,300,000	111,000
Gum, black	0·54	10·6	40	8,080	35	1,920	35	6,960	35	4,320	[illegible]	55	1,275,000	113,000
Hackberry.	0·54	10·9	40	8,380	40	1,720	40	7,870	40	4,550	80	85	1,257,000	111,000
Hemlock	0·49	9·2	40	9,520	40	2,120	40	7,480	40	4,740	80	65	1,614,000	120,000
Maple, soft	0·60	9·0	80	11,750	80	2,420	80	8,020	80	5,470	160	114	1,822,000	169,000
Maple, hard	0·68	7·6	82	15,870	82	3,320	82	11,610	82	7,060	164	124	2,009,000	135,000
Mahogany, true ..	0·48	11·4	35	8,500	35	1,940	35	6,380	35	3,780	—	—	1,252,000	117,000
Mahogany, African..	0·52	12·7	20	8,070	20	2,000	20	5,730	20	3,770	—	—	1,261,000	144,000
Mahogany, Philippine	0·53	10·7	25	10,160	25	2,310	25	10,670	25	5,980	50	90	1,820,000	169,000
Magnolia	0·59	9·9	40	9,830	40	2,340	40	10,000	40	5,740	80	98	1,704,000	135,000
Oak, white ..	0·64	10·1	75	9,440	75	1,920	75	7,260	75	3,950	150	90	1,085,000	106,000
Oak, red	0·59	9·3	115	8,500	115	2,070	115	5,480	115	3,610	230	80	1,289,000	120,000
Pine, white	0·43	10·2	35	7,920	40	1,770	40	5,640	40	3,870	80	52	1,274,000	99,000
Poplar, yellow ..	0·50	9·0	120	8,800	120	1,920	110	7,380	120	4,520	240	52	1,501,000	114,000
Redwood	0·41	11·2	65	7,900	65	1,500	120	5,100	65	3,000	130	48	1,211,000	118,000
Sycamore	0·56	10·0	80	10,920	80	2,380	80	8,840	80	5,480	160	79	1,042,000	135,000
Spruce, Sitka ..	0·41	8·0	63	7,280	63	1,540	63	7,150	63	3,150	126	75	1,716,000	98,000
Walnut, black ..	0·58	8·7	80	11,850	80	2,660	80	7,640	80	5,100	160	77	1,664,000	144,000

* Parallel and perpendicular refer to the direction of the grain of the faces relative to the direction of the application of the force.

† Specific gravity based

TABLE II.—TENSILE STRENGTH OF PLYWOOD AND VENEER.

Species.	*No. of Tests.* (a)	*Moisture of Test;‡ Per Cent.* (b)	*Specific Gravity of Plywood.** (c)	*Tensile Strength of 3-Ply Wood† Parallel to Grain of Faces. Lb. per Square Inch.* (d)	*Tensile Strength of Single-Ply Veneer.‡ 1½. (d) Lb. per Square Inch.* (e)
Birch	200	8·5	0·67	13,240	19,860
Ash, black ..	80	9·1	0·57	6,200	9,300
Ash, commercial white	120	10·5	0·61	6,700	10,050
Basswood	160	9·6	0·41	6,300	9,450
Beech	120	8·6	0·67	13,000	19,500
Cedar, Spanish ..	80	11·8	0·43	5,220	7,830
Cherry	40	9·9	0·49	6,920	10,380
Chestnut	40	11·7	0·43	4,430	6,640
Cottonwood ..	40	9·5	0·48	7,540	11,310
Douglas fir ..	110	8·4	0·4[illegible]	5,630	8,440
Elm, cork	35	11·7	0·59	9,840	14,760
Elm, white ..	120	8·9	0·53	6,460	9,690
Gum, red	102	8·5	0·54	7,780	11,670
Gum, cotton ..	80	10·3	0·49	6,260	9,390
Maple, soft ..	80	9·0	0·60	8,020	12,030
Maple, sugar ..	82	7·6	0·68	11,610	17,420
Oak, red	115	9·3	0·59	5,480	8,220
Oak, white ..	75	10·1	0·54	7,260	10,890
Poplar, yellow ..	80	8·8	0·50	7,130	10,690
Redwood	65	11·2	0·41	5,100	7,650
Sycamore	40	10·2	0·56	9,180	13,770
Spruce, Sitka ..	40	7·9	0·41	4,900	7,350
Walnut, black ..	80	9·7	0·58	7,640	11,460
Pine, white ..	40	10.2	0·43	5,640	8,460
Mahogany, Philippine	25	10·7	0·53	10,670	16,000
Mahogany, true ..	35	11·4	0·47	6,380	9,570
Mahogany, African	20	12·7	0·52	5,370	8,060

* Specific gravity based on oven-dry weight and volume at test.
† Based on total cross-sectional area.
‡ Based on assumption that centre ply carries no load. Data based on tests of three-ply panels with all the plies in any one panel same thickness and species.

TABLE III.—THICKNESS FACTORS FOR VENEER.

(*a*) Veneer thickness for same total bending strength as birch.
(*b*) Veneer thickness for same weight as birch.

Species.	G — *Average Specific Gravity of Species from Bulletin 556 and Other Sources.**	*Specific Gravity of Glued Plywood as Tested.**	*Per Cent. Moisture as Tested.*	S — *Unit Bending Strength Compared with Birch. Average of Cols. 5 and 6 in Table I.*	Ks — *Thickness Factor for same Total Bending Strength as Birch.* $\sqrt{\frac{100}{S}}$	Kw. — *Thickness Factor for same Weight as Birch.* $\frac{0.67}{G}$
1	2	3	4	5	6	7
Birch, yellow ..	0·63	0·67	8·5	100	1·00	1·00
Ash, black ..	0·50	0·48	0·2	47	1·46	1·26
Ash, commercial white ..	0·58	0·61	10.6	66	1·23	1·09
Basswood ..	0·38	0·41	9·6	42	1·54	1·66
Beech	0·63	0·67	8·6	96	1·02	1·00
Cedar, Spanish ..	0·34	0·41	13·3	41	1·56	1·85
Cherry	0·51	0·49	9·9	70	1·19	1·24
Chestnut ..	0·44	0·43	11·7	33	1·74	1·43
Cottonwood ..	0·43	0·48	9·5	51	1·40	1·47
Douglas fir ..	0·44	0·45	8·4	55	1·35	1·43
Elm, cork ..	0·66	0·59	11·7	68	1·23	0·95
Elm, white ..	0·51	0·59	8·9	56	1·33	1·24
Gum, red ..	0·49	0·54	8·5	58	1·31	1·29
Gum, cotton ..	0·52	0·4[illegible]	10·3	49	1·43	1·21
Gum, black ..	0·52	0·54	10·6	52	1·38	1·21
Hackberry ..	0·54	0·54	10·9	53	1·37	1·17
Hemlock ..	0·42	0·49	9·2	61	1·28	1·50
Maple, soft ..	0·48	0·60	9·0	74	1·16	1·31
Maple, hard ..	0·62	0·68	7·6	100	1·00	1·02
Mahogany, true	0·49	0·48	11·4	54	1·36	1·29
Mahogany, African	0·46	0·52	12·7	53	1·37	1·37
Mahogany, Philippine	0·57	0·53	10·7	65	1·24	1·11
Magnolia ..	0·51	0·59	9·9	63	1·26	1·24
Oak, white ..	0·69	0·64	10·1	[illegible]	1·30	0·91
Oak, red ..	0·63	0·59	9·3	55	1·35	1·00
Pine, white ..	0·39	0·43	10·2	50	1·41	1·62
Poplar, yellow ..	0·41	0·56	9·0	56	1·33	1·54
Redwood ..	0·36	0·41	11·2	49	1·43	1·75
Sycamore ..	0·50	0·56	10·0	69	1·20	1·26
Spruce, Sitka ..	0·38	0·41	8·0	46	1·47	1·66
Walnut, black ..	0·57	0·58	10·2	76	1·15	1·11

* Specific gravity based on oven-dry weight and volume at test.

Relative Splitting Resistance.—In Column 13 of Table I. is given the relative splitting resistance of various types of

FIG. 12.—APPARATUS FOR DETERMINING RESISTANCE OF PLYWOOD TO SPLITTING.

plywood, as measured by the amount of work required to split a 5-inch square test panel in the apparatus illustrated in Fig. 12. This testing device consists essentially of a sharp-

pointed plummet or weight that can be dropped from a given height, until the test panel is split. The point of the plummet is first embedded slightly in the centre of the panel; the weight is then raised to a certain height and dropped. The procedure is repeated until final failure occurs. The amount of work done is the product of the weight of the plummet, and the total distance through which it has fallen.

As has been previously noted, resistance to splitting is of importance, principally in connection with the fastening of plywood along its edges by means of screws, nails, or bolts. Incidentally, it is important to add that tests have demonstrated the great superiority of screws over any form of nails, a screw being more effective than a nail twice its length.

TABLE IV.

COMPARISON OF STRENGTH OF THREE-, FIVE- AND SEVEN-PLY YELLOW BIRCH PLYWOOD. ALL PLIES OF SAME THICKNESS IN ANY ONE PANEL.

No. of Plies.	*Av. Sp. Grav.*†	*Av. per Cent. Moist.*	*No. of Tests.*	*Column-Bending Modulus in pounds per square inch.*		*Tension in pounds per square inch.*		*Average Splitting Resistance compared to 3-ply Birch for the same Plywood Thickness in per Cent. of 3-ply.*
				*Parallel.**	*Per-pend.**	*Parallel.**	*Per-pend.**	
3	·68	6·1	80	19,100	3,700	14,400	7,900	100
5	·67	6·6	25	14,700	6,800	13,100	8,600	143
7	·70	7·1	23	14,300	7,900	12,900	9,300	212

It will be noticed in Table I. that the splitting resistance of the various species is expressed as a percentage of that of yellow birch. In all the plywood tests this wood has been taken as a standard, and in Table III. certain properties of other species are also expressed as percentages of the corresponding properties of yellow birch. Table IV. gives the

* Parallel and perpendicular refer to direction of grain of faces relative to direction of application of force.

† Specific gravity based on oven-dry weight and volume at test.

results of tests made to determine the effect of using panels of more than three plies. The various factors entering into this type of construction have already been discussed. In Table II. are listed the tensile strengths of single-ply and three-ply veneer of various species. Table III. gives the thickness of a sheet of veneer of any species of wood that will have the same weight as a unit thickness of yellow-birch veneer, information of considerable interest to designers. It should be noted that in this table only the relative densities of the woods themselves were considered in computing the thickness factor, and not the densities of the glued-up panels. Hence, no account is taken of variations in the amount of glue that different species of wood will absorb.

This, as a rule, is greater for open-grained than for heavy, dense woods, such as maple and birch. The thickness of any panel that shall have the same strength in bending as a yellow birch panel can be calculated from the thickness factors found in Column 6 of Table III. These factors were obtained as follows:

$$M = \frac{S_1 B D_1^2}{6} = M_2 = \frac{S_2 B D_2^2}{6} \therefore D_2$$

$$= d_1 \sqrt{\frac{S_1}{S_2}}$$

If d_1 is taken as unity, S_1, the strength of yellow birch in bending, as 100, and S_2 as a percentage of S_1, the thickness factor $K_s = \sqrt{\frac{100}{S_2}}$ and $d_2 = d_1 \cdot K_s$. It should be emphasized that the ratio of core to total thickness must be the same for both the birch panel and the one for which the calculation is being made. Also, difference in the number of plies, and in the total thickness of the proposed panel, may affect this relation somewhat.

In Table V. are given the weights in ounces per square foot of different thicknesses of various species of wood used in aeroplane construction. Using the value for weight per

TABLE V.—WEIGHTS OF VENEER.

In Ounces per Square Foot of One Ply. Veneer Thickness in Inches.

Species.	Sp. Gr. Oven-Dry based on volume Air Dry.	Air-Dry Moisture Content per Cent.	1/100	1/80	1/64	1/60	1/55	1/48	1/40	1/32	1/28	1/24	1/20	1/16	1/12	1/10	1/8	1/6	3/16	1/4
Ash, black	·50	10·4	·42	·52	·65	·69	·76	·87	1·04	1·30	1·49	1·74	2·08	2·60	3·47	4·16	5·20	6·94	7·81	10·41
Ash, white	·64	8·7	·53	·67	·83	·89	·97	1·11	1·33	1·67	1·90	2·22	2·66	3·33	4·44	5·32	6·66	8·88	10·00	13·32
Basswood	·38	8·4	·32	·40	·49	·53	·58	·66	·79	·99	1·13	1·32	1·58	1·98	2·64	3·16	3·96	5·28	5·94	7·92
Beech	·63	11·2	·52	·66	·82	·87	·95	1·09	1·31	1·64	1·87	2·19	2·62	3·28	4·37	5·24	6·56	8·74	9·84	13·12
Birch, yellow ..	·63	9·6	·52	·66	·82	·87	·95	1·09	1·31	1·64	1·87	2·19	2·62	3·28	4·37	5·24	6·56	8·74	9·84	13·12
Butternut	·39	7·6	·32	·41	·51	·54	·59	·68	·81	1·02	1·16	1·35	1·62	2·03	2·71	3·25	4·06	5·42	6·09	8·12
Cherry	·51	9·2	·42	·53	·66	·71	·77	·88	1·06	1·33	1·52	1·77	2·12	2·65	3·54	4·25	5·31	7·08	7·97	10·62
Cottonwood	·43	4·7	·36	·45	·56	·60	·65	·75	·90	1·12	1·28	1·49	1·79	2·24	2·98	3·58	4·47	5·97	6·71	8·96
Elm, white	·51	8·8	·42	·53	·66	·71	·77	·88	1·06	1·33	1·52	1·77	2·12	2·65	3·54	4·25	5·31	7·08	7·97	10·62
Gum, black	·52	7·2	·43	·54	·68	·72	·79	·90	1·08	1·35	1·55	1·80	2·17	2·71	3·61	4·33	5·42	7·32	8·12	10·82
Gum, cotton	·52	6·1	·43	·54	·68	·72	·79	·90	1·08	1·35	1·55	1·80	2·17	2·71	3·61	4·33	5·42	7·32	8·12	10·82
Gum, red	·49	11·3	·41	·51	·64	·68	·74	·85	1·02	1·28	1·46	1·70	2·04	2·55	3·40	4·08	5·10	6·80	7·66	10·20
Hackberry	·54	9·2	·45	·56	·70	·75	·82	·94	1·12	1·40	1·61	1·87	2·25	2·81	3·75	4·49	5·63	7·50	8·44	11·24
Maple, silver	·48	8·2	·40	·50	·62	·67	·73	·83	1·00	1·25	1·43	1·67	2·00	2·50	3·33	4·00	5·00	6·66	7·50	10·00
Maple, sugar	·62	10·5	·52	·65	·81	·86	·94	1·08	1·29	1·61	1·85	2·15	2·58	3·23	4·30	5·16	6·46	8·60	9·69	12·91
Oak, red	·63	10·9	·52	·66	·82	·87	·95	1·09	1·31	1·64	1·87	2·19	2·26	3·26	4·37	5·24	6·56	8·74	9·84	13·13
Oak, white	·69	11·5	·57	·72	·90	·96	1·05	1·20	1·44	1·80	2·05	2·40	2·87	3·59	4·79	5·74	7·18	9·58	10·78	14·37
Poplar, yellow ..	·41	6·1	·34	·43	·53	·57	·62	·71	·85	1·07	1·22	1·42	1·71	2·13	2·84	3·41	4·27	5·69	6·40	8·54
Sycamore	·50	9·2	·42	·52	·65	·69	·76	·87	1·04	1·30	1·49	1·73	2·08	2·60	3·47	4·16	5·20	6·94	7·82	10·41
Walnut, black ..	·57	4·8	·47	·59	·74	·79	·86	·99	1·19	1·48	1·70	1·98	2·37	2·97	3·96	4·75	5·94	7·92	8·91	11·87
Cypress	·43	9·0	·36	·45	·56	·60	·65	·75	·90	1·12	1·28	1·49	1·79	2·24	2·98	3·58	4·47	5·97	6·72	8·96
Fir, Douglas	·44	9·4	·37	·46	·57	·61	·67	·76	·92	1·15	1·31	1·53	1·83	2·29	3·05	3·66	4·58	6·10	6·87	9·16
Hemlock	·42	8·6	·35	·44	·55	·58	·64	·53	·87	1·09	1·25	1·46	1·75	2·18	2·91	3·50	4·37	5·83	6·56	8·74
Pine, longleaf ..	·66	9·2	·55	·69	·86	·92	1·00	1·15	1·37	1·72	1·96	2·29	2·75	3·44	4·58	5·50	6·88	9·16	10·32	13·75
Pine, sugar	·37	11·4	·31	·39	·48	·51	·56	·64	·77	·96	1·10	1·28	1·54	1·93	2·57	3·08	3·85	5·14	5·78	7·70
Pine, western yellow	·41	10·8	·34	·43	·53	·57	·62	·71	·85	1·07	1·22	1·42	1·71	2·13	2·84	3·41	4·27	5·69	6·40	8·54
Pine, white	·39	9·9	·33	·41	·51	·54	·59	·66	·81	1·02	1·16	1·35	1·62	2·03	2·71	3·25	4·06	5·42	6·09	8·12
Spruce, Sitka ..	·38	8·9	·32	·40	·49	·53	·58	·66	·79	·99	1·13	1·32	1·58	1·98	2·64	3·16	3·96	5·28	6·94	7·92
Mahogany, African ..	·46	5·6	·38	·48	·60	·64	·70	·80	·96	1·20	1·37	1·60	1·92	2·39	3·19	3·83	4·79	6·38	7·18	9·58
Cedar, Spanish ..	·34	7·3	·26	·35	·44	·47	·51	·59	·71	·88	1·01	1·18	1·42	1·77	2·36	2·83	3·54	4·72	5·31	7·08
Mahogany, True (Central American) ..	·49	7·9	·41	·51	·65	·63	·75	·85	1·02	1·23	1·46	1·70	2·04	2·55	3·50	4·08	5·10	6·80	7·66	10·20

Weight of glue per square foot. Blood albumen about 0·3 oz. Certus about 0·4 oz.

square foot for a single layer of glue, the total weight of a plywood panel of any thickness, number of plies, or combination of woods can be readily calculated. The results will be as accurate as normal variations in the density of any one species will permit. Here again, however, a slight error is introduced by neglecting variations in the amount of glue absorbed by different woods.

All the tables reproduced in this book were prepared by the Forest Products Laboratory for the Bureau of Aircraft Production

CHAPTER IV

DESIGN OF VARIOUS AEROPLANE PARTS OF PLYWOOD.

Wing Ribs.—Tests have demonstrated that for chord lengths up to 75 inches, which with an R.A.F. 15 section would give a maximum depth of 4½ inches, in the type of construction which employs spruce capstrips, and a plywood web, suitably lightened by holes, is fully as efficient and strong as any built-up or trussed rib, and in addition is more reliable and easier to construct than these types. That there is a limit, however, beyond which the trussed construction is superior to the plywood is obvious, but only more extended experimentation can determine what this limit is. In the webs of plywood ribs two types of cut-outs are used, the circular and the elongate; the latter may be oval, or often nearly rectangular, with a length two or three times its depth. Since the vertical members of the web serve to carry compression and horizontal shear, and to prevent buckling of the web, as a whole, it is usually best to have the grain of the face plies vertical. This is an illustration of the principle that the grain of the outside plies should be in the direction of a column load. Furthermore, as a function of the web is to act with the flange or capstrip in carrying both compression and bending, it is best to have the core, in which the grain runs parallel to the capstrip, form a large proportion of the total web. Where low-density woods are used in both the faces and the core, the ratio of core to total thickness should be about 1 to 2; and where high density faces are used with a low density core, this ratio may increase to 2 to 3. Among the light woods, Spanish cedar has proved most satisfactory

for rib construction; while, in the heavier species, combinations of yellow birch or maple faces with basswood or poplar cores are most suitable. Within the range of chord lengths which have been tested, the following thicknesses have been found to give good results: For Spanish cedar throughout, $\frac{1}{45}$-inch face and $\frac{1}{16}$-inch core; for birch outside plies and poplar core, $\frac{1}{85}$-inch faces and $\frac{1}{13}$-inch core.

Fuselage Skin.—Plywood in fuselage construction may be used merely as covering, or as reinforcement for a truss that is designed to carry either the entire load or a large portion of it. Or, if the fuselage is of the all-veneer type, the plywood shell itself, strengthened by the longerons, carries all the load.

When plywood is used in conjunction with a fuselage truss, it is important that it should not wrinkle or buckle. This tendency is more pronounced when the plywood has to lie flat than when it is curved. To decrease wrinkling or similar distortion, the core of the plywood is made relatively thick, and of a low density wood like poplar or basswood, while the face plies are of thin mahogany or birch. In the first application of plywood to fuselage trusses it served merely as a covering to replace linen. Any strengthening it afforded was incidental and was neglected in computing the longerons and wires of the truss. This was, of course, uneconomical. In later designs the plywood was made slightly heavier and stiffer, and could therefore be depended upon to carry shear stresses, to afford lateral support to compression members, and to bind together and stiffen the entire truss. It was found that all diagonal bracing wires could be omitted, and the size of the longerons considerably decreased. The use of diagonal struts, running from the lower longeron at the points of attachment of the chassis struts and flying wires, to distribute the stresses from these members to several points on the upper longeron, is advisable. The ease with which a fuselage of this character can be built, together with its comparative lightness, makes it a close competitor of the all-veneer body.

One of the chief advantages of the latter type is its high aerodynamic efficiency due to the excellent streamling that can be obtained, and to the fact that changes in the attitude of a plane do not sensibly increase the resistance of such a faired body. In the veneer fuselage the skin resists all the vertical and horizontal shear, and together with the longerons it carries the bending moment produced by air loads on the tail surfaces, or by dynamic loads. This second function determines that the grain of the face plies shall be longitudinal with respect to the axis of the body, and that of the core transverse.

Spruce plywood, because of its lightness and stiffness, has given excellent results, particularly in designs of fairly good depth and moderate length. But for the fuselages of larger, heavier planes, especially those that are relatively shallow or unusually long, a stronger wood, such as elm or birch, is better. In many instances a combination of elm faces and basswood core is most suitable.

Since the bending moment increases rapidly forward of the rear cockpit, it has been found economical to use more plies in the part of the fuselage extending from just after of the rear cockpit forward to about the centre of the engine section, than in the rear portion of the body. In a comparatively heavy fuselage, for example, this rear section is usually of three-ply veneer, and the critical section forward of the rear cockpit of five-ply. The purpose of the heavy construction near the engine section is to resist the greater shearing stresses produced by the engine and fuel tanks. Where the outer plies become unnecessary they taper down to a feather edge. For smaller bodies the skin is three-ply at the critical section and two-ply towards the rear. In this case fabric is often used between the plies, because of the greater toughness and stiffness that it imparts to the skin.

With this general type of fuselage the skin is divided into four longitudinal sections, the top, bottom, and sides. These sections may be in turn spliced transversely at one or more points. The chief function of the top and bottom

portions of the skin is to resist bending moment, that of the side sections to resist shearing stresses. The longitudinal sections join at the longerons to which plywood is glued, and screwed or nailed. A scarf joint is considered superior to a butt joint, largely because it stands weathering better. In making transverse splices in the plywood, it is the best practice to employ a long, screwed scarf joint having a slope of approximately 1 to 25, which, with $\frac{3}{32}$ inch plywood, for example, forms a lap of about $2\frac{1}{2}$ inches. Such a joint would usually be made at a bulkhead. Fig. 8 shows both longitudinal and transverse splices.

The ordinary thickness for the veneer in either the three- or five-ply construction is $\frac{1}{32}$ inch for each ply. In general fuselage work the thickness of the core is usually about 50 per cent. that of the plywood.

Beside the type of veneer fuselage which has just been described, another kind is being further developed, properly known as the monocoque type. A body of this character can be made almost perfect aerodynamically, owing to the fact that it can be built to conform to practically any contour desired. Structurally, a monocoque body acts like a shell. It is characterized by its rigidity, and resistance to distortion. Though light longerons are used, they do not play a very important part in carrying stress. In the same way, the bulkheads in the rear portion of the body are reduced in number to about three, and serve solely to stiffen the structure. It is possible to build such a fuselage for a weight considerably less than that of any other type. Unfortunately, owing to the large amount of labour required in its construction, this type as yet is expensive. Methods may be evolved that will simplify the present process.

The general method of construction is as follows: First a heavy wood form is built up which is the exact shape of the body. This is made in two symmetrical halves. When the form is ready, the work of putting on the veneer is begun There are two general methods for building up the body. The customary process is illustrated by the well-known L.W.F

fuselage and is quite reasonable in cost. With this type thin veneer strips 4 to 6 inches in width are wound spirally about the form so as to make about one turn in the length of the body. After this first layer of veneer is complete, cloth tape some 2¼ inches wide is wound over the veneer in a continuous strip, lapped about ¼ inch, and glue applied. Another layer of veneer is now laid, wrapped around the body in a spiral of the same degree but opposite in direction to the first. On top of this comes a second layer of tape wound as before. The third and last layer of veneer is now applied with the grain longitudinal. After the structure has dried three or four days, the mould, which with this method of construction is not in two halves but is collapsible, is removed. One layer of Utica sheeting, applied to the outside of the body with dope, forms the finish. Spruce veneer has been found very satisfactory. A usual thickness is $\frac{1}{32}$ to $\frac{1}{16}$ inch. In general, transverse sections of such a fuselage are symmetrica about two axes. It is not practicable with this type to form the veneer into sharp curves, and therefore the fairing of the lower wing into the body, or the construction of the fin integra with the body, is very difficult.

The second general method carries out still further some o the principles involved in the construction just described. I is probable that better results in every way can be obtaine in a body built according to this later process. However, o account of the amount of labour entailed, it is a method no adapted to large scale production. Some important detail are still being developed. In this process, the veneer in long narrow strips not more than 2 inches wide is wound on eac half form in a tight spiral of such degree that the strip make an angle of approximately 45° with the longitudinal axi These strips are crowded close together and are lightly tacke down to hold them in place. On completion of this laye the second is begun. The strips now run at right angles t those forming the inside layer. As they are laid, Certus joi glue is applied between them and the first layer. Immediately, the strips are butted up close against each other and secured

firmly in place by short, light nails every 4 or 5 inches, driven through a little 1-inch cleat of plywood. After the glue has thoroughly dried these nails and cleats are pulled off, and the form is ready for the third layer of strips, laid with glue in the same manner as before and at right angles to the strips in the second layer. When this step is completed a fourth layer of strips is applied, again at right angles to the strips in the adjacent layer. On the drying of these last strips and the removal of the nails, each half the shell may be readily removed from the form and carefully trimmed along the joint lines. The two parts of the shell are now ready to be fitted together. The splice, which occurs at the bottom and top, is made by an inside, laminated keelson, $2 \times \frac{5}{16}$ inches, to which each half the shell is securely screwed and glued. The edges of the shell are butted together, thus forming a regular butt joint with a single cover plate. The last step in the process is the application of a layer of sheeting, which is put on with hot glue, and after drying is doped and varnished. The plies forming the shell are of soft wood like poplar or spruce, each ply being about $\frac{1}{16}$ inch in thickness.

Bulkheads.—In the forward part of the fuselage the bulkheads that support the engine and gasolene tanks and receive stresses from the lift wires are of heavy construction. To secure maximum homogeneity a large number of plies, each of $\frac{1}{16}$ or $\frac{3}{32}$ inch thickness, are used. The total thickness of such bulkheads will ordinarily be between $\frac{3}{4}$ and 1 inch. If great strength is desired, birch or maple veneer is employed, but on lighter work spruce is used successfully. It is common practice when the bulkhead is of spruce, or some similar wood, to have all the plies of the same species of wood and of the same thickness, but frequently a combination of a strong, heavy wood and a light wood is advantageous.

Another more recent type of bulkhead which is much lighter than that just described is a form of built-up, truss construction, in which the stresses are carried by solid spruce members. These are connected, and built into one structure by two light sheets of three-ply veneer, which form flanges for the spruce

columns, one sheet being glued to each face of the bulkhead. Reference to Fig. 13 will make the construction clear. The gains with this type of bulkhead are due to the smaller amount

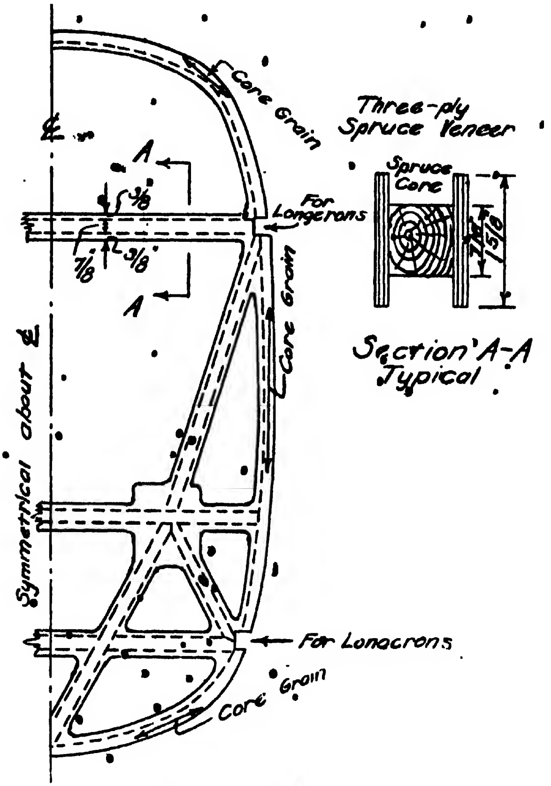

FIG. 13.—BULKHEAD.

of glue necessary, and to the fact that, because all the grain of the compression members runs in the direction of the stress, the material is most effectively used.

In veneer fuselage construction, the bulkheads in the rear act principally as stiffening rings in preventing distortion of the skin. As they carry only these secondary stresses it is

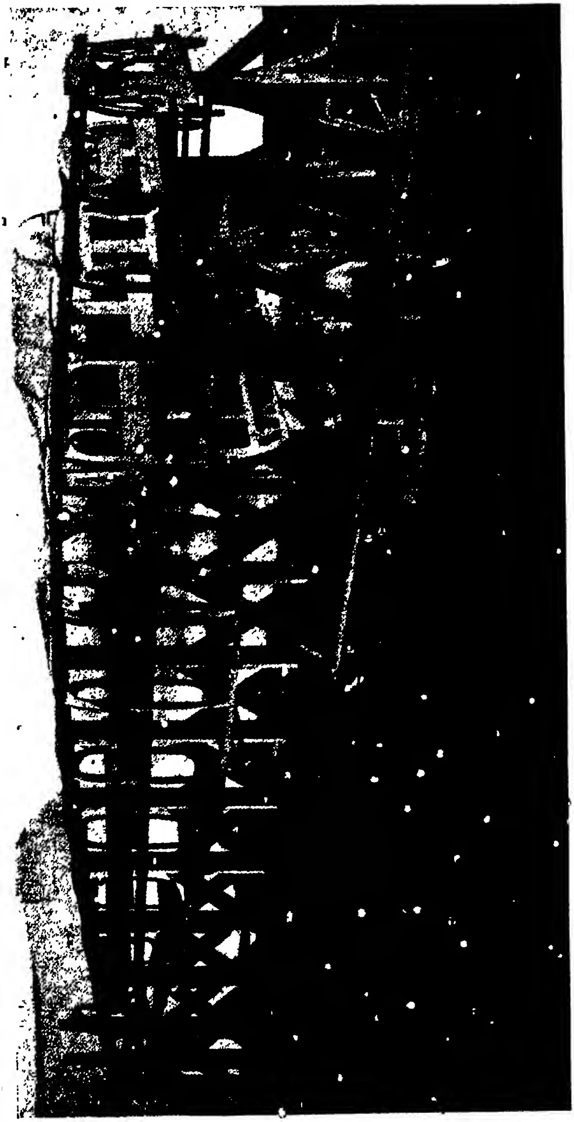

FIG. 14.—BULKHEADS AND LONGERONS OF VENEER FUSELAGE ASSEMBLED ON JIG READY FOR APPLICATION OF SKIN.

possible to make them light. Five-ply spruce of $\frac{3}{8}$ inch total thickness, or five-ply mahogany and poplar of the same thickness, for instance, is suitable for most work. Fig. 13 illustrates some of the various features that have been discussed.

Covering for Wings and Control Surfaces.—Plywood, when used to replace fabric on aerofoils, has several advantages. One of these is the elimination of sag between ribs, this distortion being considered detrimental to the efficiency of the aerofoil. Another advantage is that with plywood there is but very slight possibility of its tearing loose from the wings, as sometimes occurs with fabric. Again, plywood braces and stiffens the wing structure, distributes the stresses and, if not too thin, adds materially to the structural strength of the wing, making it possible to omit internal drift bracing, and to reduce the size of the spars. On the other hand, the plywood may warp or wrinkle, though proper design and care in the method of application should prevent this trouble. Even the lightest plywood developed up to the present weighs at least 2 to 3 times as much as doped fabric. Probably the best, very thin plywood so far designed is constructed of Spanish cedar, and has a total thickness of $\frac{1}{32}$ inch. This makes it too thin to add directly to the structural strength of the wing. Its principal use would be on control surfaces, on the centre section of the main wings, and on the upper surface of these wings from the leading edge back to the front spar.

Unless some great improvement occurs in the design of plywood for wing covering and in its application, it cannot be used on modern planes on account of its excessive weight.

Spars.—Because of the shortage, during the war, of suitable spruce for spars, many experiments have been made to develop a plywood spar. No such section has ever approached the efficiency of the solid spruce spar. This is due to the large increase in weight caused by the glue. The best types of laminated spar produced are the box section, with solid spruce flanges and about $\frac{3}{16}$ inch three-ply webs, and the I-section with solid flanges and a web of three, or possibly five, thick laminations. The utilization of material of small section and

inferior quality is the advantage sought by the use of plywood in spars. It can, however, be more easily obtained in built-up spars than in laminated ones. Spruce is a material that is most commonly employed for spars, although birch is frequently used for the faces of the webs in box spars. The face plies in this type of spar have their grain horizontal. The total thickness of each web varies from $\frac{3}{8}$ to $\frac{1}{4}$ inch, depending on the depth of the spar, while the core thickness is about half this amount.

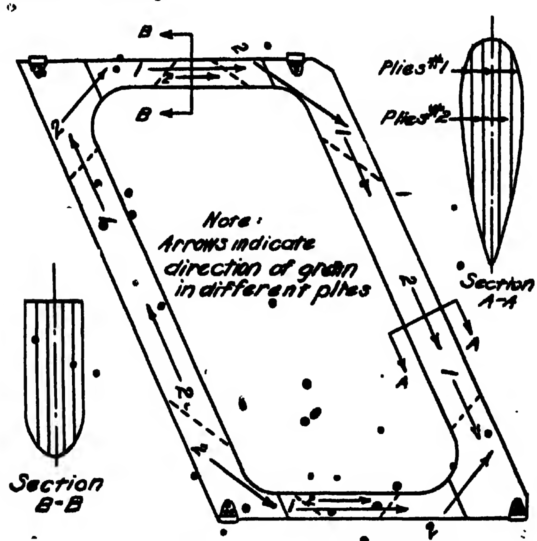

FIG. 15.—PORTAL INTERPLANE STRUT.

Struts.—In order to minimize the effect of spiral or cross-grain in spruce, a laminated construction is sometimes used in struts. Since the grain of all the laminations runs in the same direction, this type of structure is not plywood in the true sense. There are usually but 4 to 6 laminations, each being $\frac{1}{4}$ to $\frac{3}{8}$ inch in thickness. The extra weight of these struts due to the glue is a disadvantage.

Certain kinds of strut frames, such as the "N" type for

cabane struts, or the portal for interplane struts (Figs. 15 and 16), which are capable of taking moment at the corners, and so may replace diagonal or incidence wires, are a combination of laminated and plywood construction. In each member of the frame, for the greater part of its length, the grain of all the laminations is parallel to the direction of the stress, but at the intersection of the members the laminations are dovetailed, producing a plywood construction in which the grain of the adjacent plies is nearly at right angles. A unit frame of this type has considerable rigidity, but is appreciably heavier than the usual combination of single struts and wires. From the military

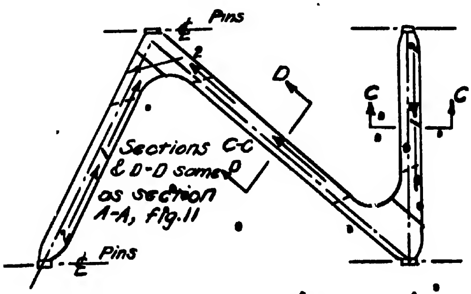

FIG. 16.—CABANE OR CENTRE SECTION STRUT.

point of view, one of its chief advantages is its ability to transmit by torsion the load from either the front or rear lift trusses, should one of the trusses be shot away, to the uninjured truss. The elimination of drift and incidence wires reduces to a certain extent the air resistance, especially with high speed planes. Another advantage of considerable importance obtained with this type of bracing is the ease which which a wing cell may be aligned. The stagger of the wings, and the decalage, if there is any, is practically fixed. However, in case it is desirable to alter the stagger for some reason, this feature is a disadvantage.

CHAPTER V

THE MANUFACTURE AND USE OF GLUES IN AEROPLANE CONSTRUCTION

THE development of a waterproof glue which should meet the necessary strength requirements and be thoroughly reliable has been one of the most important and difficult problems in our aeroplane programme. At the close of 1917, the only glue that was accepted as satisfactory for the better grade of joint work was hide glue. And it did not possess any material waterproofing qualities, despite various attempts to make it water-resistant by the addition of certain chemicals, but had to be carefully protected from all moisture by several coats of varnish or shellac. Casein and blood-albumin glues were mentioned in a survey of various available glues, issued by the Forest Products Laboratory, in the fall of 1917, when they took up the study of aeroplane glues for the Government. Both these, however, were still in the experimental stage, and were neither dependable nor of sufficient strength. Since then the Laboratory has carried on extensive development work, and in testing has co-operated closely with various manufacturers throughout the country who have been engaged on this problem. Though the results were at first discouraging because of the severity of the deterioration tests required, yet within the last six months such progress has been made in the improvement of glue that it has been conclusively demonstrated that both casein and blood-albumin glues, when properly manufactured and applied, are equal in strength to all but the finest hide glues, are, for all practical purposes, waterproof, and are uniform and reliable. Casein glue, particularly, will be a very important future factor, not alone in aeroplane construction, but in all high-grade joint work on which hide glues have heretofore been employed.

The present article treats each of the important glues in turn, briefly describing its nature and process of manufacture, and laying special stress on the mixing and application of the glue and the precautions to be observed to secure the best results. This article is based principally upon technical reports prepared for the Bureau of Aircraft Production.

Classification of Glues

Glues may be divided into the following general groups: the so-called animal glues—which include hide, bone, and sinew glues—blood-albumin, casein, fish, and vegetable glues. The three animal glues are made from scraps of hide, green bones, and sinews of cattle; blood-albumin glue from coagulated blood; casein glue from curdled milk; fish glue from fish offals, bladders, and membranes; vegetable glues from certain plant growths and substances, such as cassava-root, gums, and dextrines. A further important classification divides adhesives into true glues and cements; the former on setting merely give up their excess water and do not undergo any permanent chemical change; while the latter not only lose their excess water, but alter their chemical nature by changes that cannot be reversed. This distinction further classifies glues as non-waterproof and waterproof, respectively. Glues may again be differentiated, according to their nature and the methods used in their application, as solid or liquid glues, and hot or cold glues.

Animal Glues

Physical and Chemical Nature.—Glue is the first product of the hydrolysis of animal connective and elastic tissues. (Hydrolysis is a chemical reaction that occurs between a salt and water, in which the water is decomposed and an acid and a base, or an acid and a basic salt, are formed.) When heated with water, these tissues lose their peculiar structure, swell, and finally dissolve. Upon cooling, this solution jellies, and dries into a horny, translucent mass, of a colour, varying with the purity of the stock, from pale yellow to dark brown.

This dry glue will redissolve in hot water and the solution possesses strong adhesive qualities. No essential difference exists between glue and commercial gelatin, so extensively used in the preparation of foods and drugs. The latter, being more carefully made from selected stocks, is of lighter colour and contains fewer impurities. These impurities consist of slight amounts of mineral matter, and, sometimes, grease, free acid, alkali, odoriferous substances, and certain nitrogenous materials grouped under the name of "non-glue." Of these mucin, an impurity present in the original glue stock that should be removed by the preliminary treatment of the stock, is thought to be the cause of the "foaming" of glue. In addition to mucin, the non-glue contains nitrogenous decomposition products, produced by the hydrolysis that occurs when glue is subjected to prolonged heating. None of these substances possess any adhesive qualities. The formation of such products is the explanation of the rapid deterioration in the strength of over-heated glue. Both gelatin and glue swell in cold water, but do not dissolve until the water is heated. Their difference in adhesive power and their similarity in chemical and physical nature are difficult to account for. Glue contains two essential constituents: glutin, an amorphous, odourless, tasteless, protein substance, soluble in water and of great adhesive strength; and chondrin, similar to glutin, but derived largely from cartilaginous and young bone tissues, and not equal to glutin in binding power. Chondrin, though not having as great gelatinizing properties as gelatin, is much more viscous and adhesive. Glutin is more abundant in hide glues, chondrin in bone glues, a fact that accounts for the superiority of the former class of glues.

Manufacture of Hide Glue.—Clippings from the hide, also the tail, ear, and head pieces, form the bulk of the raw material used for hide glue. No tanned skin or parts that have begun to spoil can be utilized. Briefly summarized, the process of glue-making from either hide, bone, or sinew consists of three steps: first, washing the stock and treating it with lime to

remove extraneous material (with bone stock, the material, after being washed, is usually crushed and extracted with dilute acid before it is limed); next, boiling the stock to convert the glue-forming substances into a glue solution which is concentrated, and then jellied by cooling; lastly, slicing, and drying this jelly to form dry, cake glue. Though the process, as outlined, is very simple, any variation in the many factors involved produces marked differences in the glue.

A somewhat more detailed description of the manufacture is as follows: The glue stock, wet, or dried and salted, is washed, and then steeped for several weeks in milk or lime in wooden vats or cement pits. Frequent stirring of the material with long, forked sticks is necessary. The mass swells, and the fats are converted into lime soap, while the hair, flesh, and blood are separated from the hide and partly dissolved. The stock is now thoroughly washed in tubs, with mechanical stirrers to remove all lime, lime soap, and dirt. Dilute hydrochloric, or, better, sulphuric acid that both plumps and bleaches the stock, is used to remove the last trace of lime. After any excess of acid has been washed away, and the water dried or pressed out, the material is ready for cooking to change the collagen into glue. During this process the time and temperature must be carefully watched, since long continued cooking or actually boiling lowers the quality of the glue. Grease and lime soaps rise and are skimmed off. Solid matter (hair, dirt, etc.) sinks, and the liquor is drawn off through it. As all the stock is not dissolved in the first liquor, it is cooked several times more in fresh waters to extract all the glue. The first run yields the best glue. Usually, all the liquors are mixed to secure uniformity. Open vats, heated by steam coils, are generally used in this rendering process.

Should the liquor be too thin to jelly, it is concentrated in vacuum pans, then run into coolers—relatively small, galvanized iron vessels – and chilled by refrigeration at 32° F. In twelve to twenty-four hours the solution jellies. It is now turned out on a table, cut into slices $\frac{1}{8}$ to $\frac{1}{4}$ inch thick by

tight wires in a frame, and the slices placed in single layers on wire frames that are run into drying rooms from which sunlight is excluded. During this drying period the glue must be carefully watched, for it is either very apt to mould or liquefy through bacterial action in too low temperatures or if the temperature rises above 95° to 105° F. it is liable to melt. But in clear, cold weather, owing to the low humidity, the temperature in the drying room may rise to 110° F. In the summer, very little glue is made owing to the impossibility of drying the films. Should wet glue be frozen and afterwards dried, it becomes spongy and porous. One day is required for drying, and then the films are ready to be broken or ground in a disintegrator.

Manufacture of Bone Glue.—Fresh, green bones are the raw material for bone glue, which is very similar to hide glue. The bones are first sorted, then passed through a mill which cracks them slightly, and from there taken to the extracting plant for the removal of fat. This operation may be performed by open boiling, by digestion with steam at forty pounds pressure, or by extraction with solvents. The last method is in general use because it is most efficacious. Boiling leaves a good deal of fat in the bones, and the second method removes, not only the fat, but also a large portion of the glue-yielding substances. Benzine is the most common solvent. After extraction, the next step is treatment with dilute hydrochloric acid (sp. gr. 1·05) to dissolve the calcium phosphates and carbonates. The cartilaginous material is now washed with lime-water to remove any acid. When the washing is completed the mass is boiled in water or steamed in a digester until dissolved. Any grease that forms is skimmed or filtered off. The glue liquor is then run into shallow vats where it is clarified by the addition of alum. After ten minutes' boiling it is allowed to settle, before being drawn off into cooling vessels, refrigerated, and dried as previously described. Frequently, for the lower-grade glues, benzine-extracted bones are directly boiled or steamed without the removal of the dirt and grease. After the glue solution

is sufficiently concentrated it is strained through cloth bleached by sulphurous acid, and evaporated at 140° F. *in vacuo*, or in open troughs with half-submerged steam coils.

The process used in making sinew glue is very like that for hide glue.

Fish glue is made by boiling, at 230° F., fish heads, tails, and fins. Since it has very weak jellying properties, it is ordinarily made into liquid glue. The offensive odour of this glue is destroyed by creosote or oil of sassafras.

Either fish or animal glues can be made into liquid glues by treatment with acetic, nitric, or hydrochloric acid, a process by which their power of gelatinizing is lost. The adhesiveness of such a glue is not materially changed, and it does not require heating.

Preparation and Use of Animal Glues.—Very frequently a high-grade glue will give very poor results, simply because it has been misused in some way. It is therefore necessary to emphasize strongly that with all glues, for the highest grade work, precautions and directions given in the discussion of the mixing and application of a glue should be followed both strictly and intelligently. On unimportant work a reasonable degree of latitude is permissible.

The required amounts of glue and cold water must be weighed out in the proportions that have been previously determined for that particular glue, as described later in the specifications. If the glue is in the form of cakes, flakes, or ribbons, it should be broken up into small pieces about the size of peas and soaked, in a covered vessel with the proper amount of cold water, until every particle is thoroughly softened. Occasional stirring is necessary to insure the water's reaching every bit of glue, for if any lumps remain hard the prolonged heating, necessary to melt them, seriously lowers the quality of the glue. Even for powdered glue, the time of soaking must be at least two hours.

The softened glue is transferred to water-jacketed glue pots in which it is melted as quickly as possible without overheating. The best working temperature of the glue is 140° F.,

never above 150° F. The glue pots should be kept covered, when not in actual and continuous use, to prevent the escape of water from the glue and the formation of a surface scum. Any scum that may form must be removed. Never melt glue over an open flame or by the injection of live steam, because the local overheating injures the glue strength. Glue which has been heated for eight hours or longer must not be used. Likewise, any glue that has been heated at any time, on any day, must be rejected and not used again. The glue solution, once it has been heated, should never be allowed to cool, for reheated glue has not the same tenacity as a fresh solution.

The room in which hot glues are applied should be free from draughts, and as warm as healthful working conditions will permit. The wood should be uniformly dry, and at least as warm as the room to prevent a sudden chilling and setting of the glue. The wood should, however, not be heated to too high a temperature, since hot wood readily absorbs moisture from the glue, leaving it dry, and thereby lowering its elasticity. The wood surface should "fit" perfectly, be lightly toothed with a fine toothing plane, and be clean. The glue must be applied to both surfaces of the joint, and spread freely and as rapidly as is consistent with good workmanship. Special care must be exercised to avoid the formation of air bubbles in the joint, which break the continuity of the glue film. These are due to carelessness in applying the glue or to foaming and frothing of the glue. Pressure should be applied quickly to prevent premature jellying or setting of the glue. A sufficient number of clamps must be used to distribute this pressure evenly over the entire joint that the surfaces may be in close contact at all points. The intensity of the pressure should be about 150 pounds per square inch. From five to twelve hours, depending on the character of the work, must elapse before the clamps are removed, and not for twenty-four hours may any sudden strain be put upon the joint. If the glued surface is very large, or if there are many laminas of wood, provision should be made for properly drying the wood. In the case of all hot glues, parti-

cularly, care must be used in maintaining sanitary conditions in the mixing-room and glue-room; all glue pots, containers, and brushes must be washed at the close of each day's work; all scraps of glue about the floors and tables must be removed. Unless these precautions are rigidly observed fresh glue is liable to infection by bacteria which seriously impair its quality. Good glue has a clean odour. Decomposed glue must be rejected.

Hide glue of good quality, in spite of certain disadvantages, is recognized as being superior in strength to any other animal or vegetable glue. It is, therefore, used for propeller and all other high-grade joint work. Because of its lack of waterproofness it must be thoroughly protected by varnish or shellac. Bone and sinew glues find use in less important work: vegetable glues are extensively used for furniture; fish and other liquid glues where strength or pliability are less necessary.

Egg and Blood Albumen

Chemical Nature.—The white of an egg is called albumen, and its chief constituent is what is known chemically as albumin, a viscous, nitrogenous substance, similar to the albumin of blood-serum. Egg albumen is made up of 84·0 per cent. water, 11·9 per cent. albumin, 3·6 per cent. fat, etc., and 5 per cent. ash. (In further discussion the general term albumen will be used to mean albumin.) Albumens combine with both acids and bases to form acidic or basic salts, albuminates. With water they form perfectly clear odourless solutions.

Manufacture of Egg Albumen.—Eggs are broken and the whites carefully separated from the yolks. To obtain the clear albumen the whites are strained through silk gauze lining the drum of a centrifugal machine, and allowed to settle for thirty to forty hours. (The drums of this machine must be lead lined to prevent chemical action.) An alternative method of clearing the albumen is to cool it in iron vessels for five to six days at a low temperature; a little tannic or acetic

acid is sometimes used in the clarification. The clear albumen is dried as rapidly as possible in a stream of dry air or *in vacuo* under 120° F. (above this temperature the albumen turns yellow). Within four to six hours this process is completed, and the albumen is obtained in the form of thin, clear, elastic sheets. About 100 to 125 eggs are required to yield a pound of the dry albumen.

The methods of producing *blood albumen* are very similar to those just described. Fresh blood from cattle is spread in shallow dishes, and a separation occurs between the fibrin of the blood and the pale yellow serum. After this is complete, the serum is strained through silk gauze lining the drum of a centifrugal machine. As with the egg albumen it is allowed to settle thirty to forty hours, when the albumen should be quite clear. It is then dried in the manner outlined above, and forms flakes, varying in colour from grey to black according to the purity. The purest is of a greyish yellow colour. The blood from one cow will yield slightly less than a pound of the dry albumen.

A very pure albumen is obtained by forcing the serum through charcoal filters and precipitating the albumen by basic lead acetate. After washing, the precipitated lead albuminate is decomposed by carbonic acid and the lead removed by sulphuretted hydrogen. The albumen is then filtered and dried as before.

Albumen Glues

Preparation.—Formulæ for the preparation of these glues are still kept secret, both by the trade and the laboratories working on glue development. The dried albumen of course forms the chief constituent and to it are added ammonia and lime. In preparing the glue the dry albumen is soaked for about $1\frac{1}{2}$ hours, and then stirred in a glue mixer for a few moments. Ammonia is added, the mixture again stirred a short time, and the lime in dry form slowly introduced while the stirring continues at low speed. After standing about an hour the glue is carefully poured from under any scum that may have formed on the top and is ready for use.

Application.—Albumen glues must be applied hot, and the precautions necessary with all hot glues have to be observed. The room should be warm and free from draughts, and the wood surfaces at room temperature or above. A machine spreader is used in applying the glue, and special hot presses are required for pressing and drying the glued parts. A considerable degree of care and skill is necessary for satisfactory results. Attention should be called to the very deleterious effects of foaming with albumen glues. Foaming is largely due to the air that is ground into the glue by the spreader. With extra thick spreads of glue the pockets of air formed during the pressing are larger than with thin spreads. Wherever such a pocket occurs there is no contact between the faces of the joint. Foaming seriously impairs the strength and waterproofing properties of albumen glues.

Like casein glue, albumen glues are not glues within the strict meaning of the term, but are cements; that is, upon setting their hardening is due, not merely to the evaporation of water in the glue, but to changes in their chemical composition. The presence of water will not, as in the case of animal glues, cause them to soften after setting has once taken place, because the chemical changes that have occurred cannot be reversed. Albumen glues are therefore practically waterproof when properly mixed and applied. They are also very strong, even superior to hide and casein glues under the best conditions, but because of the care that must be used in their application albumen glues are not so reliable as other types. Their chief use is in the manufacture of plywood. Blood-albumen glue is much more widely used than egg albumen, since it is less expensive.

Casein

Chemical Nature.—Casein, the chief constituent of casein glue, exists in fresh milk, in a state of suspension, as colloid and is so finely divided that it can be separated by filtration only with great difficulty. Eighty-five per cent. of the protein of milk consists of this substance. What is called casein o

milk appears to be a compound of casein with lime that may be regarded as generally a weak acid. Casein can be obtained from milk in two ways: by treating the milk with an acid, or by curdling it with rennet. When milk is acted upon by an acid the lime casein compound is split up, and paracasein is precipitated in the form of curd. Casein combines with strong acids, acting in their presence like a weak base. In the curdling of milk by rennet, first the enzyme of rennet splits the lime casein into paracasein, the curd, and whey albumin, then coagulation follows if lime salts are present. "Self-soured" or "natural sour" casein is similar to that produced by an acid. Milk is spontaneously soured by lactic acid, produced by the action of lactic acid bacteria on milk sugar. Considerable differences in physical and chemical properties exist between acid and rennet precipitated curd. The former does not contain any lime salts, because these are all dissolved by the acid. The rennet curd is more elastic and is not sticky.

Reference to the Government specifications on casein, given later, show the general proportions of some of the constituents. The percentages of the elements present in cow-milk casein, from analysis of a pure sample, are as follows:

	Per Cent.
Carbon	52·9
Oxygen	22·8
Nitrogen	15·6
Hydrogen	7·0
Phosphorus	0·85
Sulphur	0·77

Manufacture of Industrial Casein.—As indicated above there are two general methods for the precipitation of paracasein: the first and more important is the acid, or natural sour process; the second the rennet process. This latter method has not been approved by the Government. Acid curd is precipitated from the skimmed milk by lactic acid, or by either dilute sulphuric or hydrochloric acid. The yellowish precipitant is redissolved in alkali (sodium bicarbonate) and reprecipitated with dilute acetic acid. The

curd then is well washed and pressed, after which it is stirred to pulp with water (100 parts curd to 50 parts water). When this operation is completed it is steamed or cooked twenty-five to thirty minutes in a wooden vat with about 150 parts of a 1 per cent. solution of soda to remove the lactic acid and butter fat. Upon heating, the mass forms a thin, milky fluid which is transferred to a separate vessel to cool and there precipitated by dilute nitric acid. The casein collects at the bottom, the supernatant liquor is drawn off, and the casein is rinsed with water. The casein is allowed to settle in the water, which is then very gently poured off. This operation is repeated until the wash water is neutral, when the casein is drained on filter cloths, pressed, and dried on trays in drying chambers at 120° to 140° F. One hundred parts curd yield forty-five parts of purified casein, free from lactic acid and butter fat. If the procedure just outlined is carefully followed, no trouble should be encountered in meeting the Government requirements as to acidity, or fat and moisture contents.

Ejector Method for Casein Manufacture.—The latest modification of the natural sour or lactic acid process is known as the ejector method. It consists in precipitating and collecting together or isolating the casein particles by means of live steam passed through the curdled milk. The comment of the Forest Products Laboratory on this process is given below.

Casein can be made successfully from skim milk with the ejector method of precipitating the curd, but care must be taken in allowing the skim milk to curdle before heating, or a tough, rubbery curd, impossible to handle, will result. When skim milk is allowed to curdle by the formation of lactic acid and without agitation, then there is no trouble in getting a clear and quick separation of the curd which can be handled well in every respect. The curd from naturally soured skim milk, separated by the ejector method of heating, is not only handled as easily as that precipitated with sulphuric acid, but is not nearly so tough nor so hard to grind.

The quality of casein made by the ejector method is superior in many ways to that made with the acid and cooked-sour methods. It shows better strength, dissolves more readily, and retains a fluid, viscous body at room temperature, giving it better working properties. When dissolving acid and cook-curd casein, complete solution is retarded by the formation of a heavy, short, viscous body, which, upon cooling, has a decided tendency to congeal and lose its fluidity, more especially the cooked-curd casein, making it very difficult to mix well with other solutions in the cold.

Casein Glue

Chemical Nature.—In all the various formulæ used in the preparation of this glue the main constituents are casein, lime, and sodium silicate. In the presence of water the alkali reacts with the casein to form new compounds. The waterproofness of casein glue is due to the fact that after the glue has once set the chemical changes which occur during the mixing and setting cannot be reversed. From the analyses (made by the Chemical War Service Laboratory) of two typical casein glues can be obtained an idea of the various constituents and their relative proportions.

	Le Grandville Glue	C. W. S. Laboratory Glue
Casein	36·00	44·65
Calcium hydroxide	23·80	27·90
Sodium silicate	17·00	14·85
Gum arabic	5·50	7·55
Moisture	5·30	5·05
Calcium carbonate	8·00	
Ammonia (free)	1·25	
Iron, aluminum, magnesium (as oxides)	1·50	
Undetermined	1·65	
	100·00	100·00

The "Le Grandville" glue was a new, French, propeller glue; the C.W.S.L. glue one that was developed by the Laboratory as an equivalent of the French glue. The casein

used in the Laboratory glue was designated as "self-soured," "extra-fine," casein, and the lime was technically pure.

Since the special methods of manufacture of casein glue as well as the formulæ employed are still trade secrets, the procedure followed by this Laboratory is of interest. One pint of gum arabic was dissolved in five pints of 40 per cent. commercial water-glass (sodium silicate) and evaporated over a water bath till dry enough to grind. After grinding to 50-mesh, the silicate gum-arabic mixture was thoroughly mixed with calcium hydroxide of 150-mesh size and casein of 40-mesh size in the following proportions: casein 40, alkali 25, gum mixture 20. This mixture dissolves readily in cold water, more easily in fact than the "Le Grandville" glue, and furthermore it does not "gel" as quickly as the latter. The amount of water added to the mixture was 10 parts (by weight) of dry glue to 22 parts water.

Mixing of Casein Glue.—To obtain satisfactory results with casein glue it is of extreme importance that the glue be properly mixed and applied. The directions issued by the best manufacturers with each brand of glue can be relied upon, and should be carefully followed.

Thorough mixing before use of the contents of a freshly opened barrel of prepared glue is advisable in all cases, because in shipment the heavier ingredients of the glue tend to separate out. The contents of the barrel, or barrels, are emptied into a box of suitable size and turned over with a clean shovel until the mass is uniform throughout.

Rapid stirring during the first few minutes of mixing is necessary with casein glues to prevent the formation of lumps. For this reason the slow machines used for mixing animal glues are unsatisfactory. The best type is a vertical, compound movement power mixer of variable speed, similar to the cake mixers used by bakers. In such a machine the glue is mixed in a relatively small, detachable kettle that is easily removed and cleaned. The small size of the kettle makes it possible to mix up no more than will be used before the glue hardens so that it cannot be spread. Except for larger work, the

glue should be furnished the men in one-pint, enamelled iron cups. Copper, brass, or aluminum vessels should not be used for mixing casein glues, as the alkali in the glues attacks these metals. To prevent spattering of the glue outside the mixing kettle a metal hood, fitted with a feed hopper, will be found effective.

Since, with very slight modifications, the procedure used in mixing Certus glue can be adapted to other casein glues it will be given here. The requisite amounts of water and glue, which are in the proportion of 18 parts by weight of water to 10 parts of glue, are carefully weighed out in separate containers. Owing to slight variations in the dry glue, this proportion may have to be altered slightly to give a glue of uniform consistency. The water is poured in the mixing kettle; the machine speeded up to about 350 to 450 r.p.m. of the blade, which for most mixers corresponds to about 140 r.p.m. of the vertical shaft, and the glue gradually introduced through the hopper. It is of great importance to avoid the formation of lumps. The rapid stirring is continued three to five minutes after the last of the glue has been added. The mixer is then stopped to permit the scraping down of any glue that may have spattered on the sides of the kettle. When this has been done the machine is again set in motion, but at a slower speed (60 to 90 r.p.m. of the shaft), and stirring kept up for at least ten minutes, or until all the fine particles of casein are dissolved. The purpose of the reduction in speed during this second mixing is to allow the escape of air bubbles that may have been whipped into the glue. Should there still be an appreciable amount of air in the glue it is advisable to permit the mixture to stand a short time before using, so that the air can separate Some casein glues require the addition of various ingredients singly, and it is necessary to change the above practice to conform to the manufacturer's directions.

On important work it is best not to make any changes in the consistency of the glue. But if the mixer is familiar with the nature of the glue being used, it is permissible to alter its

consistency before the glue has been removed from the mixing kettle. In case the glue is too thick, an extra part or two of water may be added, or if it is too thin a small amount of dry glue may be put in. Stirring at a slow speed should be kept up a few minutes until the water is thoroughly incorporated in the mixture, or the glue completely dissolved. With a glue in which the different constituents are added separately this method cannot be followed. It is possible, however, to mix up a thick glue and add this to the thin glue, but the practice is not good.

Application of Casein Glue.—The results of tests show that, at any time during its working life, good results may be obtained from normal glue. In fact, the strength of the glue increases with its viscosity. But once it has become too thick to spread properly the remaining glue must be rejected. The working life of casein glue varies with different brands; Certus is one of the more satisfactory in this respect, as usually it is workable for four to five hours after mixing. Liberal application of the glue to all the surface of both faces of the joint gives the best results. Some glue should squeeze out of the joint when pressure is applied. The clamps should be put on as soon as possible, not more than ten minutes after the spreading is begun, depending on the kind of wood, the amount of glue used, the temperature, and the glue consistency. About 150 pounds per square inch is a suitable pressure; more than this tends to squeeze the joint dry of glue.

The minimum time the joints should be kept under pressure is about three to five hours, varying with the size of the glued surface. Upon removal from the clamps the wood should be dried to remove the moisture added by the glue, particularly if varnish is to be applied. Full strength and waterproofness are not attained until about two weeks after the gluing.

The most essential precautions may be briefly summarized: (1) Mix thoroughly each barrel of glue before using. (2) Weigh the glue and water; do not measure them. (3) Avoid lumpy mixtures. (4) Avoid mixtures which are too thick or too thin. (5) Mix until all the fine particles dissolve and

a smooth mixture is obtained. (6) Do not attempt to use glue after it has become too thick to spread properly. (7) Never thin or thicken glue once it has left the mixer. (8) Keep all brushes, kettles, and pots sanitary to prevent bacterial infection of the glue.

Factors Affecting the Quality of Casein

The variations in caseins from different sources, or even in successive shipments from the same manufacturer, are often so great as to make necessary changes in standard glue formulæ if satisfactory results are to be obtained. Regulation and standardization of the processes used in the production are essential if casein glue is to be made reliable in strength and waterproofing qualities.

The Forest Products Laboratory has recently completed extensive experimental work on this subject. It was found that, for the purpose of controlling the quality of the product, the following properties serve as suitable criteria: colour, odour, fineness, and moisture, ash, nitrogen, and acid content. Their conclusions may be summarized as follows:

1. Lack of uniformity in commercial casein is due, partly to lack of care in skimming the milk, drying the curd, and grinding the casein, but largely it is due to the different methods used in precipitating the curd and to insufficient washing of the curd.

2. The fat content should be as low as possible since, though it does not affect the waterproofness of the glue, it decreases its strength in proportion to the amount of fat present.

3. The acidity should also be kept low because acid affects unfavourably both the strength and waterproofness of a glue, increases the time required to dissolve the glue, and decreases its working life

4. The fact that ash (mineral salts) is inert matter makes it undesirable.

5. Casein which will not pass a 60-mesh sieve does not dissolve readily, must be allowed to stand considerably longer

before using than finer casein, and is not of such high strength.

6. To produce casein of low acidity, low ash and high nitrogen contents the curd must be thoroughly washed; with the natural sour method three or four washings are enough; with an acid curd cooking is the only safe way.

7. The sole method at present of producing a consistent, low ash content is the so-called ejector process. Further, study of acid methods will probably develop means for better removal of the ash.

8. With care in the manufacture, and proper control of the product by chemical analysis, a uniform, commercial casein can be readily produced at the present time that will conform to these specifications:

Colour, white; ash content, 2·5 per cent. (max.) on a moisture-free basis.

Odour, sweet; fat content, 1·5 per cent. (max.) on a moisture-free basis.

Fineness, 60 mesh; nitrogen content, 14·5 per cent. (min.) on a moisture, fat, and ash-free basis.

Moisture, 8 per cent. (max.); acidity content, 2·5 cc. N/10 alkali per gram (max.) on a moisture-free basis.

Testing of Glue

Two general types of tests have been developed, each type designed to serve a different purpose. The first is primarily for the glue or aeroplane manufacturer who must have simple, inexpensive, and rapid means of checking up, from day to day, the relative quality and uniformity of his product. The second is essentially for a well-equipped, experimental laboratory for the purpose of determining, by more or less elaborate and extended quantitative tests, the suitability of certain glues for specific uses, or of developing and improving new glues. Viscosity, jelly, odour, foam, and litmus tests fall under the first head; shear strength and the various deterioration tests come under the second. In doing all testing work it is extremely important that average working

conditions be closely followed in the preparation of the test specimens, for otherwise no indication is obtained as to the actual commercial product. If comparative results are to be obtained it is necessary, in each test, not only to have the strength of the glue solution the same, but also the conditions of temperature and humidity. In the preparation of specimens for shear strength tests care should be taken to use wood of uniform quality, and to have the surfacing of the joint, the spreading of the glue, and the pressure as nearly uniform as possible.

Animal Glues.—Since these glues, even when treated with formaldehyde or potassium bichromate to render them insoluble, are only partially water-resistant, and therefore must always be protected, severe deterioration tests are seldom made on them. Most of the testing is on those properties which are indexes of the strength, covering power, and keeping qualities of the glue. The determination of the moisture content is of value in indicating the elasticity of a glue, or its power to stretch slightly without fracture. A dry glue is low in elasticity, and, though it may be very strong under steady stress, it fractures readily upon sudden application of even a small load. The moisture content varies between 5 and 18 per cent., but with a good glue it is not less than 10 per cent. The "water-absorption power" of a glue, or the amount of water a given amount of dry glue will absorb in twenty-four hours, is, to a certain extent, a measure of its quality. Generally speaking, the lower the absorption, the better is the glue. Another property that is usually indicative of the character of glue is the viscosity of a solution of specified proportions of water and glue. As a rule, glues of high viscosity are of high quality and strength; hide glue, for example, which is more viscous than bone glue, is superior to it. Another common test used to check up the quality of a glue is the determination of the consistency or strength of a jelly prepared in a specified manner. Strong glues usually have high jelly strength, though this is not invariable. The ease with which a glue may be spread, or its covering

power, is another property of much interest. This may be estimated from the water-absorption, viscosity, and jelly trength. The covering power is high when the water-bsorption is low and the viscosity and jelly strength high. The keeping quality of a glue is one more important characeristic. Decomposition is due to bacterial action, and a light acidity of the glue, which is unfavourable to the growth of bacteria, is desirable. Whether a glue is acid or alkaline s determined by testing a solution with litmus paper.

The tests mentioned above are of a qualitative nature and serve only as general guides. Below are given briefly the methods used in making the tests required by specifications for glue used on Government work.

Tests for Hide Glue.—1. The viscosity is determined by allowing 200 cc. of glue at a temperature of 140° F. to flow through an orifice. The time required for water to flow through is taken as the standard. The approved instrument for this test is the Engler viscosimeter.

2. The jelly strength is determined upon a mixture of 12 parts water to 1 part glue. The glue is soaked, melted, and poured at once into a vessel of standard shape and size. It is then allowed to stand at least fift en hours in a refrigerator at a temperature between 40° and 50° F. The test is made, either by comparing the relative strengths of two or more jellies by pressing the jelly with the fingers, or by causing a small plunger to sink down in the jelly a certain distance, and noting the weight required to do this.

3. The test for grease is made by mixing a dye with a portion of the glue and painting the mixture on a piece of unsized white paper. Should the glue contain no grease the painted streak will have a uniform appearance, otherwise it will appear mottled or spotted. An excessive amount of grease is undesirable because grease has no adhesive qualities, but a small amount helps to prevent foaming, particularly where the glue is to be used in a gluing machine in which it is agitated much more than when applied by hand.

4. The test for foam shall be made on the sample used in

the viscosimeter. The sample, after being heated to 140° F., shall be beaten for one minute with a power egg-beater, and allowed to stand one minute before the height of the foam is measured. Glue that foams badly is objectionable, because air bubbles are liable to get into the joint and reduce the area in which the glue is in contact with both the joint faces.

5. The odour of the glue when in hot solution must be sweet, and remain sweet for forty-eight hours—that is, free from any suggestion of decomposing animal matter.

6. The adhesiveness of a glue is determined by a shear strength test made according to the following specifications. The specimens used in this test shall be of maple with a shearing strength of at least 2,400 pounds per square inch, which requires a wood weighing 50 pounds, or more, to the cubic foot. The dry glue shall be mixed with that proportion of water which gives the strongest glue, and applied to the wood in a manner in accord with the best practice. The glued blocks shall be put under a pressure of about 150 pounds per square inch for fifteen to twenty hours, and when this is removed they shall be allowed to stand for six days more before testing. They shall be tested to destruction in a standard testing machine. This specification covers shear tests for animal, albumen, and casein glues.

With the exception of the last, the above tests are not used for waterproof glues.

Deterioration Tests.—Beside the shear test just described, waterproof glues are subjected to the water test. Specimens prepared exactly as for the dry shear test, and with no protective coating whatever, are soaked for fifteen hours in water at 70° F. They are then tested in shear, without any preliminary drying, within thirty minutes after their removal from the water.

For waterproof plywood panels further deterioration tests are required. (1) The boiling test: two specimens are boiled in water for twenty-four hours. The plies should show no signs of separation at the end of this time. This is an accelerated soaking test, and has largely superseded the latter;

(2) The baking test: two specimens are baked in an oven at 212° F. for twenty-four hours. The baking test may be made separately, though it is common practice to subject specimens, first to the boiling test, and then to the baking test. No separation of the corners or plies should occur in this test. (3) The soaking test: two specimens are soaked two weeks in cold water and their condition noted from time to time.

It may be said in general that panels made up with animal glues, when unprotected with varnish, will never stand the soaking, boiling, or baking tests without serious injury, and for the most part without complete failure. On the other hand, the best grades of both casein and albumen glues show very little or no deterioration under any of these, or other deterioration tests.

Strength Test Data.—In the standard shear test with maple blocks, individual specimens will give maximum glue strengths of 2,600 to 3,000 pounds per square inch, with minimum values of 1,800 to 2,200 pounds per square inch for hide, casein, and albumen glues.

The strength of glue as determined by shear tests on three-ply veneer specimens is very low by contrast. It ranges from about 150 pounds per square inch to 400 pounds per square inch under favorable conditions. They may be tested in an ordinary cement briquette testing machine, but special means of gripping the specimen must be provided, so that the pull will be kept parallel to the direction of the joint. If this is not done the plywood tends to bend, because of the eccentricity of the loading, until the pulls are in line, and failure occurs from a combination of shear and cleavage. This effect is more pronounced as the thickness of the plies, and hence the eccentricity of the pulls, increases.

Bureau of Aircraft Production Specifications for Glues

No attempt will be made to give complete, detailed specifications; only the more important requirements will be mentioned.

Hide Glue Certified for Use in Aeroplane Construction.—(1) The glue must be a high-grade glue, sweet and free from any deleterious substances. (2) The glue shall be tested, in accordance with the methods previously outlined, by comparison with a standard sample furnished by the Forest Products Laboratory, for adhesiveness, viscosity, jelly strength, grease, foam, and odour. (3) The glue used in the adhesiveness test should be mixed with water in four proportions, by weight:

Water	2	$2\frac{1}{4}$	$2\frac{1}{2}$	$2\frac{3}{4}$
Glue	1	1	1	1

(4) That proportion of water which gives the greatest glue strength shall be used. For this best proportion no specimen may fail at a load less than 2,200 pounds per square inch, and the average shearing strength must be 2,400 pounds per square inch.

Handling and Testing of Hide Glue.—This specification covers the methods and precautions to be used in the proportioning, soaking, melting, and applying of hide glue. These have been given in detail in the section treating of hide glue. A shear-strength test must be made to ascertain the quality of the glue and the character of the work being done. For test specimens, 1-inch boards, of the same class of material as used in the work on hand, shall be glued up under the same average conditions as those under which the regular work is conducted; no special precautions may be taken; these boards shall be clamped and dried, as for the usual shear test. Ten specimens shall then be cut out and tested immediately. In at least eight specimens the strength of the glue shall not be less than that of the wood.

Casein for Casein Aeroplane Glue.—(1) The casein shall be made from straight skimmed milk of low fat content, and free from starch, dirt, and other foreign material of adulterants. (2) The casein shall be precipitated by lactic acid, sulphuric acid, or hydrochloric acid methods. (3) The precipitating temperature should be about 120° F., never more than 130° F. Only sufficient acid to secure a clear separation shall be used.

The curd shall be well pressed, and dried without delay to prevent moulding. Casein made from mouldy curd will not be accepted. (4) With the sulphuric acid process of precipitation, the cooked curd method is preferred. The temperature of cooking shall be about 190° to 195° F. (5) All vats, cloths, and other apparatus employed in obtaining the curd must be washed each day the equipment is used. (6) The specifications as to the properties of casein, and the proportions of some of its constituents, follow closely the specifications suggested by the Forest Products Laboratory in the section "Factors Affecting the Quality of Casein," though allowing, in some instances, slightly more leeway.

Casein Glue for Aeroplane Construction.—(1) The certified glue shall be in the form of a powder, not coarser than 50 mesh (2) It must consist principally of certified casein. (3) The manufacturer shall prepare definite instructions for mixing the glue, and when these have been approved they must be exactly followed. (4) The test for adhesiveness shall be made on four standard shear specimens, prepared and tested in the specified regular manner. (5) The average shear strength must be 2,200 pounds per square inch, and the minimum in any single case 1,800 pounds per square inch (6) In a similar manner four more test specimens shall be made up, and subjected to the "water test" previously described. (7) The average shear strength must be 1,500 pounds per square inch, and the minimum 1,400 pounds per square inch. (8) The casein, after certification, must be properly stored in a dry sheltered place, such as is required for the storage of all glue and casein.

Application of Certified Casein Joint Glue.—The specifications regarding the mixing and application of this glue, and the precautions to be observed, are embodied in the sections describing these processes for casein glue.

Relative Merits of Different Glues

Of the animal glues, only hide glue is suited to aeroplane work. This glue possesses the advantage of being inexpen-

sive, familiar to most workmen, comparatively easy to apply, reliable if careful supervision is exercised, and of high strength. It has the great disadvantage, in many classes of work, of being difficult to protect from moisture, and of being very seriously affected if exposed to moisture. Blood-albumen glue is more in the nature of a special glue. Its chief disadvantage is that skilled workmen and elaborate machinery are required in its use. Unless conditions are very nearly right its strength is apt to be uncertain. This glue shares with hide glue the disadvantages that are associated with hot glues; for the best results, the gluing should be done in an uncomfortably warm room; care must be taken to warm the wood, and to prevent sudden chilling of the glue; because of the quick setting qualities of such glues, haste is necessary in spreading the glue and in applying pressure to the joint. On the other hand, blood-albumen glue is strong and very resistant to deteriorating conditions. For certain classes of work, as the manufacture of plywood, it is eminently satisfactory. More important than this glue is casein, because of its strength, reliability with proper care in its mixing and application, waterproofing qualities, ease of manipulation, and general adaptability to all classes of work. Some brands, however, give trouble by too rapid setting, and usually most casein glues must be mixed fresh every three or four hours. The development of this glue has been the most important accomplishment of all the research work on the subject of glues during the past year. Eventually, casein will probably largely replace other glues for general aeroplane construction, and even for propeller work.

APPENDIX I

TESTS ON THIN PLYWOOD AS A SUBSTITUTE FOR LINEN IN AEROPLANE CONSTRUCTION

THE use of thin sheets of wood properly glued together in place of linen, for aeroplane covering, has long been considered as a possibility. Veneer of some species may be cut into large sheets only $\frac{1}{80}$ inch thick. When three sheets of such thin material are glued together, a covering is obtained, whose weight compares quite favourably with that of doped aeroplane linen, so that there is some reason for considering wood as a material for covering, although at first thought it might seem to be out of the question on account of its apparent excess weight.

In view of the frequent demand for information upon the properties of thin plywood and its uses in aeroplane construction, tests were initiated at the Forest Products Laboratories of the U.S. Forest Service, at Madison, Wis., to determine the merits of thin plywood as a covering for aeroplane surfaces. While it was possible to prepare very thin sheets of three-ply wood that would be as light as doped linen, a few attempts at gluing such material soon showed that the difficulty of handling the veneer made the manufacture of plywood of this kind impracticable, at least in the present stage of the plywood industry. A few tests also showed that very thin plywood lacked toughness and tearing strength, and there seemed to be little hope of using the lightest plywood. The tests were, therefore, continued on somewhat thicker material, with the surmise that the heavier plywood might possess other properties that would compensate for its excess weight.

The relative importance of the various properties desired in

an aeroplane covering is not established. Each of the following properties is, however, of sufficient consequence to merit consideration: (*a*) Minimum weight consistent with safety; (*b*) high tensile strength; (*c*) high toughness, or resistance to blows tending to rupture the covering; (*d*) high tearing strength; (*e*) high rigidity, or minimum stretch under load; (*f*) maximum stability; (*g*) resistance to fire.

Tests made by many experimenters with the use of a variety of chemicals have shown that wood may be impregnated with solutions that render it highly fire-resistant; consequently, no special work was undertaken to treat thin plywood for this purpose.

Tests were devised to measure the quality of the material in each of the other properties mentioned above, and the results, obtained from more than two thousand such tests, are here briefly considered.

Practically all the material tested was glued at the Laboratory by the tissue process, in which a sheet of tissue, previously soaked in blood-albumen glue and dried, is inserted between two sheets of thin veneer and then pressed in a hot press to set the glue.

Among the species that may be cut into very thin veneer are Spanish cedar, mahogany, birch, sugar maple, red gum, yellow poplar, and black walnut. The veneer of these species may be satisfactorily glued by the tissue method.

Three constructions of thin plywood were prepared. First, a three-ply construction in which the grain of the centre ply was at right angles to the grain of the face plies; second, a construction in which a piece of cloth was incorporated between two veneer plies having their grains at right angles; third, a construction in which a piece of cloth was glued between two plies of veneer, whose grains made an angle of 60° with each other.

Weight

The weight of aeroplane linen given five coats of dope at the Laboratory was about 0·9 ounce per square foot, while the minimum weight of three-ply Spanish cedar made of $\frac{1}{120}$-inch

veneer was about 1 ounce per square foot. Thin plywood constructions that were considered satisfactory from the point of view of facility of manufacture, and with respect to strength and toughness, weighed slightly more than 2 ounces per square foot. In constructions of this kind a sheet of cotton cloth was glued between two sheets of this veneer, the thickness of the veneer used being about $\frac{1}{60}$ inch for low-density species, such as basswood, Spanish cedar, and yellow poplar. For high-density species, such as birch, beech and sugar maple, a veneer thickness of about $\frac{1}{80}$ inch gives a plywood weight of from 2 to 2·5 ounces per square foot. A large part of the weight of thin plywood lies in the glue.

Tensile Strength

Strips one inch wide were tested in tension, their ends being held between flat grips, in an ordinary Olsen testing machine, calibrated to read to one pound. In the case of three-ply wood, tension tests were made, both in the direction of the face grain and in the direction of the core grain. In two-ply construction, where the plies were glued so that the grain of one face was at right angles to the grain of the other face, the tests were made parallel to the direct on of the grain of each face. In two-ply construction, where there was an angle of 60° between the directions of grain in the face plies, the plywood was tested in the two directions bisecting the angles between the grains of the faces.

A two-ply construction in which the grain of one ply makes 90° with the grain of the other ply, should have the same tensile strength in the direction of the grain of each face, which is practically equal to that of the single ply of veneer. The tensile strength of birch veneer is about 20,000 pounds per square inch at 8 per cent. moisture. From this it is seen that the strength of a straight-grained ply $\frac{1}{80}$ inch thick should be about 250 pounds per inch of width, which is more than three times as great as the strength requirements of Grade A aeroplane linen. The two-ply, 90° construction described gave entirely satisfactory tensile strength. The

two-ply, 60° construction gave relatively low tensile strength. It was stronger in the direction of the grain of the veneer than in the direction in which the tests were made.

Toughness

In addition to being strong in resisting a tensile load slowly applied, aeroplane covering must also offer resistance to sudden blows, such as would result from striking brush on landing, or dropping tools while assembling or repairing the machine. The method used by the Laboratory for measuring the toughness of thin plywood sheets is as follows: A cast-iron ball weighing 3·27 pounds is dropped upon the centre of the test specimen, which is tacked upon a frame 18 inches square inside. The ball is dropped upon the centre of the panel from various heights, beginning with a ½-inch drop, and increasing by ½-inch increments. The height of the drop at which the ball passed through the panel was recorded as the measure of toughness.

The tests showed conclusively that very thin three-ply wood, such as that made of Spanish cedar veneer $\frac{1}{150}$ inch thick, is low in toughness, and for that reason is not satisfactory as a substitute for linen. In order to improve the toughness of thin plywood made of veneer thinner than about $\frac{1}{50}$ inch, it was found necessary to incorporate a cloth fabric between the plies. Aeroplane cotton, Grade A, proved to be very satisfactory for this purpose.

Tearing Strength

When ruptured in flight by a projectile, an aeroplane covering may develop a serious tear, especially in the slip stream of the propeller, where it is subjected to the rapid succession of air pulsations. It was thought that such repeated stresses could be simulated by the whipping action of a special apparatus. The test sheets were fastened in a wooden frame. A hole through the specimen admitted a cam mounted on a motor shaft operating at 1,800 r.p.m., the

weight of the frame and sheet under test being supported by the cam. The throw of the cam caused the frame to vibrate or shake in its guide, so that the cam tore a gap in the plywood. The time to tear a gap one inch long was taken as the basis of comparison of the relative tearing resistance of the material.

The very thinnest three-ply wood made of $\frac{1}{150}$-inch veneer was unsatisfactory in tearing resistance. Thicker material, even without cotton fabric, made of veneer such as $\frac{1}{55}$-inch basswood or $\frac{1}{80}$-inch birch, proved to be much more resistant to tearing than doped linen. The addition of a cloth fabric further increased the tearing resistance.

Rigidity

In order to retain the desired theoretical aerofoil, the covering of an aeroplane wing or tail surface must be rigid—that is, it must stretch comparatively little upon the application of a distributed load, such as the air pressure.

Rigidity was measured at the Laboratory by the magnitude of the load at a given deflection, as determined by the sand-load test. The sand is retained by the frame and levelled off on the surface. The deflection at the centre of the sheet was measured at each load, and later plotted against the corresponding load in pounds per square foot of surface.

The results show what a marked difference in rigidity exists between the doped linen and thin plywood of satisfactory construction. The superiority of the thin plywood over the linen extends over the entire range of loads used (up to 70 pounds per square foot), but is most marked for the lower loads.

Stability

Aeroplane covering which becomes loose or abnormally tight, or develops waves with changing atmospheric humidities, is quite unsatisfactory. Such changes in stretch are here described under the term "lack of stability."

Stability determinations were made upon a variety of thin plywood constructions by placing out of doors the sheets tacked upon heavy frames, thereby exposing them to changes in humidity. Stability was measured in this test by changes in sag with changing humidity. A small weight was placed upon the centre of a test sheet tacked upon the frame, and the deflection at the centre of the sheet was measured. The panel was then turned over, and deflection measurements were again taken. The sum of the two deflections is spoken of as the "sag."

Thin plywood, especially when unprotected, absorbs moisture very rapidly, so that there is an appreciable loosening and tightening with changing atmospheric humidity. The tests showed the necessity of giving the sheets several coats of a good waterproof finish. Such coatings as aluminum leaf, barytes enamel, and spar varnish were tried. Their effectiveness in keeping out moisture was in the order in which they are named.

Numerous tests have shown that for a three-ply construction the shrinkage from the soaked to the oven-dry condition is somewhat greater than 0·5 per cent. across the grain of the faces, and somewhat less than 0·5 per cent. parallel to the grain of the faces.

Thin Spanish cedar plywood, covered with two coats of barytes enamel and one coat of spar varnish, changed moisture content only about 4 per cent. upon exposure to almost 100 per cent. relative humidity for a continuous period of four days. Similar material protected with an aluminium leaf coating absorbed less than 1 per cent. moisture in the same period. Unprotected plywood is, however, not as stable as doped aeroplane linen.

Conclusions

The tests indicate that while plywood sheets may be made that will compare favourably in weight with doped linen, they cannot be manufactured on a commercial scale in the present state of the plywood industry; and, furthermore,

that such very thin sheets are unsatisfactory in toughness, tearing strength, and stability.

The most promising material consists of two plies of about $\frac{1}{35}$-inch low-density veneer, such as yellow poplar, or $\frac{1}{50}$-inch high-density veneer, such as birch, glued with the grain of one ply at right angles to the grain of the other ply, and having a sheet of cotton cloth incorporated between the plies. Such material weighs almost 2·5 times as much as doped aeroplane linen, and somewhat more than this when coated with various finishes. While the weight of thin plywood of this kind is considerably greater than that of doped linen, its tensile strength is more than three times as great as the tensile strength of linen. It is far more rigid than linen, and has greater resistance in tearing. Two-ply wood, however, requires a framework or ribbing to hold it in place to best advantage, and to prevent the formation of shallow waves. Therefore, in cases where large surfaces are to be covered without supporting framework, a standard three-ply wood may be more desirable.

APPENDIX II

SEWN PLYWOOD

This plywood differs from every other material of the kind in that the component layers, after being cemented together, are actually sewn through with rows of parallel stitching The mere crossing of the grain, as in ordinary plywood, renders the material very strong, but the rows of stitching give to sewn plywood a super-added strength and stability which make it much the strongest and the lightest material yet evolved.

For over twenty years this principle has been utilised by Saunders of Cowes in the construction of boats of all descriptions. Racing motor boats (the fastest in the world, which still hold all speed records), service boats and launches for the Royal Navy, Coastguard patrol boats for the Egyptian Government, gondolas for airships, and hulls for flying boats, have been built of this sewn plywood, and have never failed to give perfect satisfaction. Recently it has been used with great success in aircraft construction—a use which is steadily growing. For aircraft and boats of all kinds, for internal or external panelling, for all kinds of domestic articles, and for many purposes in connection with rolling stock, sewn plywood possesses marked advantages over any other material.

On a test of motor-car bodies which were subjected to a temperature of 120° C. for 8 hours, there was no shrinkage, distortion, or sign of defect at all. Even such articles as suit cases can be made on mahogany "Consuta" with satisfactory results, despite the large amount of ill-usage to which they are subjected.

After many years of experiment it has now been found possible to produce this "sewn" plywood by special machinery,

and the name "Consuta" has been registered to describe it. "Consuta" plywood is being turned out on a commercial scale, and, as it is undoubtedly stronger than any other known material of equal weight, its uses are practically limitless.

It is now being produced in sheets 8 feet wide up to 60 feet long, and in thicknesses from $\frac{1}{8}$ inch up to $\frac{5}{8}$ inch. Owing

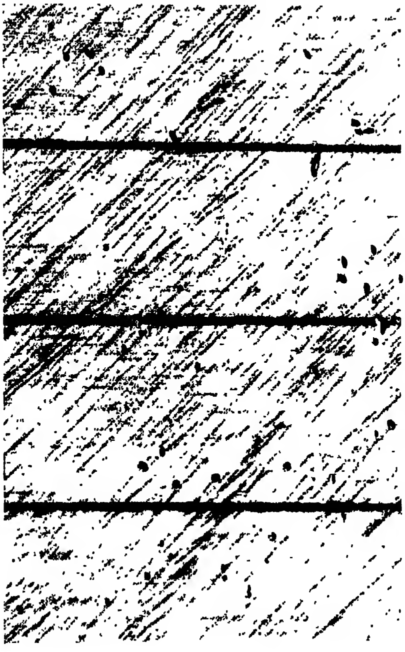

FIG. 17.—"CONSUTA" PLYWOOD.

to this width standard launches can be produced with five pieces only. The 50 foot long, 7 feet 6 inches wide, sides of "Valencia" flying boat hulls are each in one piece. In consequence of the smooth exterior these boats are five knots faster than the F. 2. A. type. Another special advantage is that the laminæ are specially laid in the direction most suitable for the particular purpose for which it is intended.

For instance, for the side of a boat, the fuselage of aircraft, or the covering of a wing, the grain would be laid in reverse diagonals, giving a girder type of construction which contributes largely to the strength and stability of the finished article. A further point is that the sheets can be made to any desired size or shape, thus preventing any waste in conversion. "Consuta" plywood is practically impervious to all atmospheric conditions. The laminæ are cemented together by a waterproof substance, and are then sewn through by machines specially constructed for the work with thread specially manufactured. The stitches run lengthwise of the material, and the rows are spaced 1¼ inches apart, as shown in Fig. 17. If the face side of the material is required to be perfectly smooth, the stitches are countersunk by a special device, and, when painted or varnished, an absolutely smooth surface is produced; when thoroughly filled and coated with either paint or varnish it becomes absolutely waterproof in every sense of the word. The pores of the wood are closed, and so coated that moisture cannot possibly reach the bare wood, and the possibility of trouble through expansion or contraction is practically eliminated.

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